THE ELEMENTARY GEOMETRY OF FUNCTION SPACE.[1]

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1. Introduction. The recent literature of mathematics contains numerous references to what is called the "geometry of function space," and at least one extended and systematic account of the subject.[2] Increased recognition of the essential identity of its elements with the leading ideas of the theory of statistical correlation is likely to make it the object of renewed attention, and there seems to be a place for an introductory treatment, dealing in simple terms with the properties of the two- and three-dimensional sections of multidimensional space which suffice for many of the purposes of statistics. A fact particularly emphasized in the following presentation is that the logical unity of geometry and analysis can be firmly established in a very few lines, and geometrical methods used thenceforth not merely to illustrate, but actually to demonstrate, the analytical relations. The simplest problems of statistics are concerned, to be sure, with finite sums rather than with integrals, and so with space of a finite number of dimensions [3] rather than with what is ordinarily called function space; the author's purpose in placing the latter in the foreground is to appeal to those students of mathematics to whom the technique of integration is more familiar, and therefore more suggestive, than that of summation. At the end of the paper it is pointed out how the corresponding work with summation, and in particular the rapid laying of a foundation for actual geometrical reasoning in n-dimensional space, can be accomplished.

2. Distance and angle in two dimensions. Let [4] $\varphi_1(t)$, $\varphi_2(t)$ be two continuous functions of t, defined for $a \leqq t \leqq b$, and such that

$$\int_a^b [\varphi_1(t)]^2 dt = 1, \qquad \int_a^b [\varphi_2(t)]^2 dt = 1, \qquad \int_a^b \varphi_1(t)\varphi_2(t)dt = 0. \tag{1}$$

All integrals throughout the paper, unless the contrary is expressly indicated, will be extended from a to b, with t as variable of integration.

Let

$$v(t) = x\varphi_1(t) + y\varphi_2(t), \tag{2}$$

[1] Based largely on a paper presented to the American Mathematical Society, as a preliminary communication, April 19, 1924; *cf. Bulletin*, vol. 30 (1924), p. 398.

[2] G. Kowalewski, Über Funktionenräume, *Wiener Sitzungsberichte, Math.-Naturw. Klasse*, vol. 120: 2a (1911), pp. 77–109 and 1435–1472. This paper will be cited below by the letter K. See also footnote attached to the first page of Kowalewski, Eine Eigenschaft der Volterra-Gruppe, the same *Sitzungsberichte*, vol. 121: 2a (1912), pp. 941–947.

[3] *Cf., e.g.*, the author's paper entitled "The trigonometry of correlation" (cited hereafter by the letter T), this MONTHLY (*1924*, 275–280).

[4] The reasoning applies, with appropriate formal changes, but without material complication, to functions of two or more variables. *Cf.* the paper K, p. 79 ff.

where x and y are arbitrary real numbers. As φ_1 and φ_2 are linearly independent,[1] because of (1), $v(t)$ is not identically zero unless x and y are both zero; and two functions v_1 and v_2, similarly expressible with coefficients (x_1, y_1) and (x_2, y_2), are not identically equal unless $x_1 = x_2$, $y_1 = y_2$. The functions v may be regarded as standing in a one-to-one correspondence with the points of a plane, referred to an ordinary system of rectangular coördinate axes.

Let $v_1 = x_1\varphi_1 + y_1\varphi_2$, and let P_1 be the point with coördinates (x_1, y_1), while O stands for the origin. Since

$$\int v_1^2 = x_1^2 \int \varphi_1^2 + 2x_1y_1 \int \varphi_1\varphi_2 + y_1^2 \int \varphi_2^2 = x_1^2 + y_1^2,$$

the square root of the left-hand integral is the distance of P_1 from the origin. If $v_2 = x_2\varphi_1 + y_2\varphi_2$ is a second function, corresponding to the point P_2 with coördinates (x_2, y_2), then $\int (v_2 - v_1)^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2$, and the square root of the integral is equal to the distance P_1P_2. If the lengths OP_1, OP_2, P_1P_2 are denoted for the moment by l, m, n, the cosine of the angle $P_1OP_2 = \theta$ is given by the formula [2]

$$\cos\theta = \frac{l^2 + m^2 - n^2}{2lm} = \frac{\int v_1^2 + \int v_2^2 - \int (v_2 - v_1)^2}{2\sqrt{\int v_1^2 \int v_2^2}} = \frac{\int v_1 v_2}{\sqrt{\int v_1^2 \int v_2^2}}. \qquad (3)$$

It is assumed here that neither v_1 nor v_2 is identically zero.

Thus integral formulas are obtained for distance and angle, in which φ_1 and φ_2 do not appear explicitly. They would be the same if v_1 and v_2 were similarly expressed in terms of any other pair of functions satisfying the conditions (1). Furthermore, while (2) of course represents only a limited class of functions when φ_1 and φ_2 are given, it is possible to express *any* specified continuous functions v_1 and v_2 in terms of a *suitably chosen* pair φ_1, φ_2, satisfying (1). If v_1 and v_2 are linearly independent, the purpose may be accomplished by setting [3]

$$\varphi_1 = \frac{v_1}{\sqrt{\int v_1^2}}, \qquad w_2 = v_2 \int v_1^2 - v_1 \int v_1 v_2, \qquad \varphi_2 = \frac{w_2}{\sqrt{\int w_2^2}}. \qquad (4)$$

If v_2 is linearly dependent on v_1, while v_1 is not identically zero, it suffices to apply the process just indicated to v_1 and $\bar{v}_2$, where $\bar{v}_2$ is any continuous function not linearly dependent on v_1. The trivial case that $v_1 = v_2 = 0$ identically can be disposed of with still greater ease. Any conclusions that may be deduced by further study of the concrete geometrical figure that has been set up will therefore be of general applicability, and will not be conditioned by the particular pair of functions φ_1, φ_2 originally chosen as a basis for the representation.[4]

[1] Suppose φ_2 were proportional to φ_1, so that $\varphi_2 = c\varphi_1$. If $c = 0$, the second of equations (1) is contradicted; if $c \neq 0$, then $\int \varphi_1\varphi_2 = c\int \varphi_1^2 = c$, and the third equation is contradicted.

[2] When $\int v_1 v_2 = 0$, so that $\theta = 90°$, v_1 and v_2 are said to be *orthogonal* to each other; this terminology is far more widely used than the definition of an angle by means of (3) in general.

[3] *Cf.* Erhard Schmidt, Zur Theorie der linearen und nichtlinearen Integralgleichungen. I. Teil: Entwicklung willkürlicher Funktionen nach Systemen vorgeschriebener, *Mathematische Annalen*, vol. 63 (1907), pp. 433–476; p. 442.

[4] The original pair can be replaced by an infinite variety of others, related to them by the formulas which define a rotation of axes in the plane.

Since the expression (3) is the cosine of an angle,[1] its absolute value can not exceed 1, a fact which, when the integrals are replaced by finite sums, is of fundamental importance in the theory of correlation. When neither v_1 nor v_2 is identically zero, the expression is equal to ± 1 if and only if the points O, P_1 and P_2 are in a straight line, and for this it is necessary and sufficient that v_1 and v_2 be proportional to each other. The sine of the angle, regarded as belonging to the range $0 \leqq \theta \leqq 180°$, is

$$\sin\theta = \sqrt{1 - \cos^2\theta} = \frac{\sqrt{\int v_1^2 \int v_2^2 - \left[\int v_1 v_2\right]^2}}{\sqrt{\int v_1^2 \int v_2^2}},$$

and the quantity under the radical sign in the numerator is therefore zero when v_1 and v_2 are proportional, being positive in all other cases, a relation which is most familiarly known under the name of Schwarz's inequality. Since the denominator is equal to $\overline{OP}_1 \cdot \overline{OP}_2$, the numerator by itself can be expressed in the form $\overline{OP}_1 \cdot \overline{OP}_2 \sin\theta$, and is equal to the area of the parallelogram having OP_1 and OP_2 for two of its sides.[2]

Under the hypothesis that v_1 and v_2 are linearly independent, let the problem be proposed of determining a constant λ so that $\int (v_2 - \lambda v_1)^2$ shall be a minimum. The function λv_1 is represented by a point Q on the line OP_1, so situated that $\overline{OQ}/\overline{OP}_1 = \lambda$. The integral is the square of the distance QP_2, and is least when Q is the foot of the perpendicular from P_2 on OP_1. When this condition is fulfilled, $\overline{OQ} = \overline{OP}_2 \cos\theta$, and

$$\lambda = \frac{\overline{OQ}}{\overline{OP}_1} = \frac{\overline{OP}_2}{\overline{OP}_1}\cos\theta = \frac{\sqrt{\int v_2^2}}{\sqrt{\int v_1^2}} \cdot \frac{\int v_1 v_2}{\sqrt{\int v_1^2 \int v_2^2}} = \frac{\int v_1 v_2}{\int v_1^2}.$$

This is, on the one hand, essentially the formula for a regression coefficient in the theory of statistics,[3] and, on the other hand, what may be called the Fourier coefficient of v_2 with regard to v_1.

To mention a less familiar problem, consider the determination of

$$w = (1 - \lambda)v_1 + \lambda v_2 = v_1 + \lambda(v_2 - v_1),$$

so that $\int w^2$ shall be a minimum. The point Q' representing w is on the line P_1P_2, and for the minimum is the foot of the perpendicular from O on P_1P_2. Then $\overline{Q'O} \cdot \overline{P_1P_2}$ is twice the area of the triangle OP_1P_2, or in other words the area of the parallelogram for which a formula has already been obtained, and the minimum value of the integral is

$$\overline{Q'O}^2 = \frac{\int v_1^2 \int v_2^2 - \left[\int v_1 v_2\right]^2}{\int (v_2 - v_1)^2},$$

[1] It is to be reiterated that, once the possibility of the geometric representation has been established for arbitrary v_1 and v_2, the various geometric relations in the figure are not merely amusing parodies of the analytical facts, but amount to actual demonstrations of them.

[2] *Cf.* K, p. 82.

[3] *Cf.*, *e.g.*, the paper T, p. 277.

a result which would be deduced analytically at considerably greater length. For λ itself, on the other hand, it must be admitted that a straightforward analytical determination is simplest.

If $w_1 = v_1 + \lambda_1(v_2 - v_1)$, where

$$\frac{\lambda_1}{1-\lambda_1} = \frac{\overline{OP}_1}{\overline{OP}_2} = \frac{\sqrt{\int v_1^2}}{\sqrt{\int v_2^2}},$$

the corresponding point Q_1' divides the side P_1P_2 of the triangle into segments proportional to the other two sides, and so is the bisector of the angle P_1OP_2. The equal angles P_1OQ_1' and $Q_1'OP_2$ have equal cosines:

$$\frac{\int w_1 v_1}{\sqrt{\int w_1^2 \int v_1^2}} = \frac{\int w_1 v_2}{\sqrt{\int w_1^2 \int v_2^2}}.$$

Conversely, the analytical verification of this equality, which involves some manual but no particular intellectual exercise, yields a proof of one of the least obvious theorems of elementary geometry. Essentially the same proof could of course be given in the notation of ordinary analytic geometry, without reference to function space.

One could proceed without limit to interpret the formulas of plane trigonometry in terms of more or less complicated integral relations. It is to be noticed, however, that whenever *three* functions are involved, they are for the present linearly dependent, and the corresponding conclusions are subject to a restriction which will disappear in many cases when the outlook is widened presently to comprehend a three-dimensional section of function space.

It is perhaps worthy of explicit mention that if the vector from the origin to an arbitrary point of the plane is used instead of the point itself as representative of a function, the addition of functions is isomorphic with vector addition, and the integral of the product of two functions is equal to the scalar product of their vectors.[1]

3. Length of arc in two dimensions. The definition of length of arc in function space, like the definitions that have preceded, can be based directly on the corresponding concept in ordinary geometry. Let $w(\xi, t)$ be a function of ξ and t, continuous for $a \leqq t \leqq b$ and for $\gamma \leqq \xi \leqq \delta$, and having a derivative with regard to ξ which is continuous over the same region. In order to keep the discussion within the bounds that have been observed hitherto, let it be supposed that $w(\xi_1, t)$, $w(\xi_2, t)$, and $w(\xi_3, t)$ are linearly dependent, if ξ_1, ξ_2, and ξ_3 are any three values in (γ, δ). If $w(\xi_1, t)$ and $w(\xi_2, t)$ are linearly independent,[2] the value of w

[1] *Cf.* K, p. 78.

[2] The still simpler case in which $w(\xi_1, t)$ and $w(\xi_2, t)$ are linearly dependent for all values of ξ_1 and ξ_2, while $w(\xi_1, t)$ is not identically zero, can be included in the discussion by a little attention to details, and will not be further treated separately. The case of identical vanishing of $w(\xi, t)$ is trivial.

corresponding to an arbitrary ξ in (γ, δ) can be linearly expressed in terms of them, in the form

$$w(\xi, t) = A(\xi)w(\xi_1, t) + B(\xi)w(\xi_2, t),$$

where A and B are continuous functions of ξ, with continuous derivatives.[1] The functions $w(\xi_1, t)$ and $w(\xi_2, t)$, like the arbitrary v_1 and v_2 previously considered, can be linearly expressed, with coefficients independent of t, in terms of a φ_1 and a φ_2 satisfying (1), so that w may be regarded as having the form

$$w(\xi, t) = \alpha(\xi)\varphi_1(t) + \beta(\xi)\varphi_2(t),$$

the coefficients once more being continuous functions of ξ with continuous derivatives.

When ξ has a specified value, w, regarded as a function of t, is represented by the point P with coördinates (α, β). As ξ goes from γ to δ, the point P describes the curve represented by the parametric equations

$$x = \alpha(\xi), \qquad y = \beta(\xi).$$

The length of this curve is

$$\int_\gamma^\delta \sqrt{[\alpha'(\xi)]^2 + [\beta'(\xi)]^2}\, d\xi. \tag{5}$$

Now

$$\frac{\partial w}{\partial \xi} = \alpha'(\xi)\varphi_1(t) + \beta'(\xi)\varphi_2(t),$$

and

$$\begin{aligned}\int_a^b \left(\frac{\partial w}{\partial \xi}\right)^2 dt &= [\alpha'(\xi)]^2 \int_a^b \varphi_1^2 dt + 2\alpha'(\xi)\beta'(\xi) \int_a^b \varphi_1\varphi_2 dt + [\beta'(\xi)]^2 \int_a^b \varphi_2^2 dt \\ &= [\alpha'(\xi)]^2 + [\beta'(\xi)]^2,\end{aligned}$$

by virtue of (1), so that the integral (5) is equal to

$$\int_\gamma^\delta \sqrt{\int_a^b \left(\frac{\partial w}{\partial \xi}\right)^2 dt}\, d\xi. \tag{6}$$

The last expression is independent of the choice of the functions φ_1 and φ_2 which serve as basis for the coördinate system, and is intelligible without reference to any coördinate system whatever. It is natural, then, to consider that a curve

[1] Since $w(\xi_1, t)$ and $w(\xi_2, t)$ are linearly independent, the determinant

$$\begin{vmatrix} w(\xi_1, t_1) & w(\xi_2, t_1) \\ w(\xi_1, t_2) & w(\xi_2, t_2) \end{vmatrix}$$

is not zero identically in t_1 and t_2. If t_1 and t_2 are given a particular pair of values for which the determinant is not zero, the equations

$$\begin{aligned} w(\xi, t_1) &= A(\xi)w(\xi_1, t_1) + B(\xi)w(\xi_2, t_1), \\ w(\xi, t_2) &= A(\xi)w(\xi_1, t_2) + B(\xi)w(\xi_2, t_2), \end{aligned}$$

can be solved for A and B, and their continuity and continuous differentiability follow from the corresponding properties of w.

in function space is defined by the function $w(\xi, t)$, and that the quantity (6) is its length.[1]

For example, suppose two functions v_1 and v_2 are given, such that $\int v_1^2 = \int v_2^2 = 1$, while $\int v_1 v_2$ is not zero, except as a special case. Let[2]

$$w = \eta v_1 + \xi v_2,$$

where η is determined as a function of ξ so that $\int w^2$ is constantly equal to 1. The direct application of the preceding work is complicated by the fact that the function $\eta(\xi)$ is not single-valued; but on the formal side it may be said that if ξ goes from 0 to 1, η going at the same time from 1 to 0, and if w, v_1, and v_2 are represented by the points P, P_1, and P_2, the variable point P describes a circular arc of unit radius connecting P_1 and P_2, so that the integral (6), extended from $\xi = 0$ to $\xi = 1$, may be expected to have the value arc cos $(\int v_1 v_2)$. It is readily verified by direct calculation that this is the case.[3]

4. Distance and angle in three dimensions. The ideas that have been illustrated above can be extended without difficulty from two dimensions to three. Let φ_1, φ_2, and φ_3 be three functions of t, continuous for $a \leqq t \leqq b$, and such that

$$\int \varphi_1^2 = \int \varphi_2^2 = \int \varphi_3^2 = 1, \qquad \int \varphi_1\varphi_2 = \int \varphi_1\varphi_3 = \int \varphi_2\varphi_3 = 0. \tag{7}$$

If the functions $v_1 = x_1\varphi_1 + y_1\varphi_2 + z_1\varphi_3$ and $v_2 = x_2\varphi_1 + y_2\varphi_2 + z_2\varphi_3$ are associated with the points P_1 and P_2 having the coördinates (x_1, y_1, z_1) and (x_2, y_2, z_2), the integral $\int (v_2 - v_1)^2$ is found once more to be equal to the square of the distance P_1P_2, and the cosine of the angle P_1OP_2 is given by (3), just as before. It is with the introduction of a third function v_3, represented by a third point $P_3 : (x_3, y_3, z_3)$, that new relations begin to make their appearance. *Any* three functions v_1, v_2, v_3, continuous in (a, b), can be linearly represented in terms

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[1] *Cf.* K, pp. 91–93.

[2] *Cf.* Ph. Frank and G. Pick, Distanzschätzungen im Funktionenraum. I. *Mathematische Annalen*, vol. 76 (1915), pp. 354–375; see pp. 355–356.

[3] Let $r = \int v_1 v_2$; the condition $\int w^2 = 1$ is equivalent to the relation $\xi^2 + 2r\xi\eta + \eta^2 = 1$. Then

$$\frac{\partial w}{\partial \xi} = v_2 + \frac{d\eta}{d\xi} v_1 = v_2 - \frac{\xi + r\eta}{r\xi + \eta} v_1,$$

$$\int_a^b w_\xi^2 dt = 1 - 2r\frac{\xi + r\eta}{r\xi + \eta} + \left(\frac{\xi + r\eta}{r\xi + \eta}\right)^2 = \frac{(\xi^2 + 2r\xi\eta + \eta^2)(1 - r^2)}{(r\xi + \eta)^2} = \frac{1 - r^2}{(r\xi + \eta)^2}.$$

By the equation connecting ξ and η,

$$(r\xi + \eta)^2 = r^2\xi^2 + (2r\xi\eta + \eta^2) = r^2\xi^2 + (1 - \xi^2) = 1 - (1 - r^2)\xi^2,$$

and the value of the integral (6), with $\gamma = 0$, $\delta = 1$, is found to be

$$\text{arc sin } \sqrt{1 - r^2} = \text{arc cos } r.$$

This calculation was the subject of a note presented to the American Mathematical Society, April 19, 1924; *cf. Bulletin* of the Society, vol. 30 (1924), p. 402. For a completely detailed presentation, it would of course be necessary throughout to distinguish carefully the determinations of the multiple-valued functions involved, noticing particularly that the range of ξ as variable of integration may be from 0 to a value $\xi_0 > 1$, and then from ξ_0 back to 1.

of functions φ_1, φ_2, φ_3, satisfying (7). It may be assumed without loss of generality that v_1, v_2, v_3 are linearly independent, since, if they are not linearly independent themselves, they can be linearly expressed in terms of functions which are; and then it suffices to define φ_1 and φ_2 as in (4), writing $w_1 = v_1$ for uniformity, and to set

$$w_3 = v_3 \int w_1^2 \int w_2^2 - w_1 \int w_1 v_3 \int w_2^2 - w_2 \int w_2 v_3 \int w_1^2, \qquad \varphi_3 = \frac{w_3}{\sqrt{\int w_3^2}}.$$

Let λ and μ be determined so as to minimize the integrals $\int (v_2 - \lambda v_1)^2$ and $\int (v_3 - \mu v_1)^2$ respectively. When λ and μ are thus fixed, let $v_2 - \lambda v_1 = w_{12}$, $v_3 - \mu v_1 = w_{13}$. The points Q_2 and Q_3 which correspond to the functions λv_1 and μv_1 are the feet of the perpendiculars from P_2 and P_3 on OP_1. If the coefficients in the expression

$$w_{12} = (x_2 - \lambda x_1)\varphi_1 + (y_2 - \lambda y_1)\varphi_2 + (z_2 - \lambda z_1)\varphi_3$$

are plotted as the coördinates of a point P_2', the segment OP_2' is equal and parallel to the segment Q_2P_2; it lies in the plane P_1OP_2, and is perpendicular to OP_1. Similarly, w_{13} is represented by a point P_3' such that OP_3' is equal and parallel to Q_3P_3. Then the angle $P_2'OP_3'$ is the measure of the dihedral angle between the planes P_1OP_2 and P_1OP_3. The cosine of this angle, represented by

$$\frac{\int w_{12} w_{13}}{\sqrt{\int w_{12}^2 \int w_{13}^2}},$$

corresponds to a coefficient of partial correlation.

Let the angle just mentioned be denoted by ψ_1, and the corresponding dihedral angles P_1–OP_2–P_3 and P_1–OP_3–P_2 by ψ_2 and ψ_3; let the angles P_2OP_3, P_1OP_3, P_1OP_2 be designated by θ_1, θ_2, and θ_3. Then ψ_1, ψ_2, ψ_3 are the angles of a spherical triangle which has θ_1, θ_2, θ_3 for its sides. The application of the law of cosines to this triangle leads to the formula by which a coefficient of partial correlation is expressed in terms of ordinary coefficients of correlation;[1] if $\cos\theta_1$, $\cos\theta_2$, $\cos\theta_3$, $\cos\psi_1$, $\cos\psi_2$, $\cos\psi_3$ are denoted by r_{23}, r_{13}, r_{12}, r_{23}', r_{13}', r_{12}' respectively,

$$r_{12}' = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}},$$

with similar formulas for r_{13}' and r_{23}'.

Let the triangle be considered drawn on the unit sphere about the origin, its vertices being at the points A, B, C, where the sphere is pierced by OP_1, OP_2, OP_3. Let D be the foot of the altitude[2] from A on the side BC, and let ω stand

[1] *Cf.* T, pp. 277–279. See also Frank and Pick, *loc. cit.*, p. 357.

[2] In this paragraph, one may be permitted to evade difficulties of intuition by assuming, as is usually done in elementary presentations of spherical geometry, that the sides of the triangle are of moderate length. While it is of course possible to make the geometrical treatment completely rigorous, the attainment of rigor at this stage is probably easier on the basis of a return to analytical methods.

for the angle DOA, measured by the arc DA. In the right spherical triangle BDA,

$$\sin \omega = \sin \theta_3 \sin \psi_2.$$

The cosine of ω, given by the (positive) square root of $1 - \sin^2 \omega$, has the character of a coefficient of *multiple* (or more specifically *double*) correlation. Since $\cos \theta_3 = r_{12}$ and $\cos \psi_2 = r_{13}'$, it is found by calculation that

$$\sin \theta_3 = \sqrt{1 - r_{12}^2}, \qquad \sin \psi_2 = \frac{\sqrt{H}}{\sqrt{(1 - r_{12}^2)(1 - r_{23}^2)}},$$

where

$$H = 1 - r_{12}^2 - r_{13}^2 - r_{23}^2 + 2r_{12}r_{13}r_{23},$$

an expression symmetrical in the r's, and

$$\sin \omega = \frac{\sqrt{H}}{\sqrt{1 - r_{23}^2}}, \qquad \cos \omega = \frac{\sqrt{r_{12}^2 + r_{13}^2 - 2r_{12}r_{13}r_{23}}}{\sqrt{1 - r_{23}^2}}.$$

It is easy now to calculate the volume of the parallelepiped having OP_1, OP_2, OP_3 for edges. Let M be the foot of the perpendicular [1] from P_1 on the plane P_2OP_3. The parallelogram determined by OP_2 and OP_3 may be taken as the base, and MP_1 as the altitude, of the parallelepiped. The angle MOP_1 is the angle between OP_1 and the plane P_2OP_3, and is the same as that which has been denoted by ω, so that

$$\overline{MP}_1 = \overline{OP}_1 \sin \omega = \overline{OP}_1 \cdot \frac{\sqrt{H}}{\sqrt{1 - r_{23}^2}}.$$

On the other hand, the area of the parallelogram is

$$\overline{OP}_2 \cdot \overline{OP}_3 \sin \theta_1 = \overline{OP}_2 \cdot \overline{OP}_3 \sqrt{1 - r_{23}^2}.$$

So the volume V of the parallelepiped is

$$V = \overline{OP}_1 \cdot \overline{OP}_2 \cdot \overline{OP}_3 \sqrt{H} = \sqrt{H \int v_1^2 \int v_2^2 \int v_3^2}$$
$$= \sqrt{(\int v_1^2 \int v_2^2 \int v_3^2 - (\int v_1 v_2)^2 \int v_3^2 - (\int v_1 v_3)^2 \int v_2^2 - (\int v_2 v_3)^2 \int v_1^2 + 2 \int v_1 v_2 \int v_1 v_3 \int v_2 v_3)}.$$

The result may be expressed by the equation

$$V^2 = \begin{vmatrix} \int v_1^2 & \int v_1 v_2 & \int v_1 v_3 \\ \int v_2 v_1 & \int v_2^2 & \int v_2 v_3 \\ \int v_3 v_1 & \int v_3 v_2 & \int v_3^2 \end{vmatrix};$$

the square of the volume is equal to the Gramian determinant [2] of the given functions v_1, v_2, v_3.

[1] Since M is the point of the plane P_2OP_3 which is nearest to P_1, the corresponding function is the linear combination of v_2 and v_3 which gives the best approximation to v_1 in the sense of the method of least squares. *Cf.* the article on "Partial and multiple correlation" by T. L. Kelley, in the "*Handbook of mathematical statistics*" edited by H. L. Rietz, p. 139.

[2] *Cf.* K, p. 82.

The same result can also be deduced from the ordinary determinant formula for the volume of a parallelepiped in solid analytic geometry. Let v_1, v_2, v_3 be expressed in terms of a set of functions φ_1, φ_2, φ_3, satisfying (7), by means of the equations

$$\begin{aligned} v_1 &= x_1\varphi_1 + y_1\varphi_2 + z_1\varphi_3, \\ v_2 &= x_2\varphi_1 + y_2\varphi_2 + z_2\varphi_3, \\ v_3 &= x_3\varphi_1 + y_3\varphi_2 + z_3\varphi_3. \end{aligned}$$

If the first equation is multiplied by φ_1 and integrated from a to b with regard to t, the right-hand member reduces to x_1, because of (7), and it is found that $x_1 = \int v_1\varphi_1$. The other coefficients may be determined explicitly in similar fashion. Then, by the formula of solid analytic geometry referred to,

$$V = \pm \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix} = \pm \begin{vmatrix} \int v_1\varphi_1 & \int v_1\varphi_2 & \int v_1\varphi_3 \\ \int v_2\varphi_1 & \int v_2\varphi_2 & \int v_2\varphi_3 \\ \int v_3\varphi_1 & \int v_3\varphi_2 & \int v_3\varphi_3 \end{vmatrix}.$$

If these two equivalent expressions for V are multiplied together row by row, the first element in the first row of the product is $\int v_1(x_1\varphi_1 + y_1\varphi_2 + z_1\varphi_3) = \int v_1^2$, and the other elements are found similarly to be those of the Gramian determinant.

5. Transition from integrals to sums. No effort will be made here toward the further development of three-dimensional geometry in function space, nor toward the interpretation of "geometrical" figures of higher dimensionality; as to the latter extension, while the forms of words can be carried over, suitably revised and amplified, the picture is of course no longer truly geometrical, according to the common-sense understanding of the term. The student who is accustomed to thinking of function space as a background for the theory of integral equations and of functions of infinitely many variables may object with justice that the present matter-of-fact description of a thin slice of it fails entirely to convey the sense of adventure, not to say exhilaration, that properly belongs to quasi-geometrical reasoning in an infinite number of dimensions; but there is profit of a different sort in recognizing the possibility of building up an extensive system of relations without the introduction of any startling novelty.

In fact, there has been no real need of any mention at all of space of many dimensions, except for the sake of showing the relation of the subject matter to the ideas ordinarily called up by the use of the more general terms. In so far as the reasoning has been geometrical, it has been essentially confined to the space of ordinary geometry. This will be brought out still more clearly in the treatment of finite sums, to which reference was made in the introduction. If the reader is in the habit of thinking in terms of the general notion of function, he will already have made the substitution of an index k ranging from 1 to n for the variable t going continuously from a to b, as independent variable, and the

corresponding substitution of sums for integrals.[1] Otherwise, he will probably find it advantageous to make a fresh start, with a new notation, more immediately suggestive of that ordinarily used in the formulas of statistics. The beginnings of such a theory are outlined in the concluding paragraphs below, with studied omission of any reference to "space" of more than three dimensions. For brevity, a separate treatment of two-dimensional relations is passed over, and the discussion is concerned with three dimensions from the start.

6. The geometry of statistical formulas of summation. Let $(x_1, x_2, \cdots, x_n)$, $(y_1, y_2, \cdots, y_n)$, and $(z_1, z_2, \cdots, z_n)$ be three sets of n real numbers each, with regard to which it will be assumed that no set consists entirely of zeros, and, for convenience, that the three sets are linearly independent, though failure of the last requirement would have no more serious consequence than to call for a few additional words of explanation. For each value of k from 1 to n, let[2]

$$A_k = x_k, \qquad B_k = y_k \sum A_k^2 - A_k \sum A_k y_k,$$
$$C_k = z_k \sum A_k^2 \sum B_k^2 - A_k \sum A_k z_k \sum B_k^2 - B_k \sum B_k z_k \sum A_k^2,$$
$$a_k = A_k / \sqrt{\sum A_k^2}, \qquad b_k = B_k / \sqrt{\sum B_k^2}, \qquad c_k = C_k / \sqrt{\sum C_k^2}.$$

Here, and subsequently, it is understood that the sign $\sum$ refers always to summation from $k = 1$ to $k = n$. It is readily verified by direct calculation that

$$\sum a_k^2 = \sum b_k^2 = \sum c_k^2 = 1, \qquad \sum a_k b_k = \sum a_k c_k = \sum b_k c_k = 0. \tag{8}$$

The x's, y's, and z's can be expressed in terms of the a's, b's, and c's by equations of the form

$$x_k = \xi_1 a_k + \eta_1 b_k + \zeta_1 c_k,$$
$$y_k = \xi_2 a_k + \eta_2 b_k + \zeta_2 c_k,$$
$$z_k = \xi_3 a_k + \eta_3 b_k + \zeta_3 c_k,$$

where $\xi_1, \cdots, \zeta_3$ are independent of k. Representations of the same form, with different coefficients, are possible in terms of an infinite variety of sets of a's, b's, and c's, satisfying (8); and any such[3] sets of quantities may be taken as basis for the discussion. The fact that $\eta_1 = \zeta_1 = \zeta_2 = 0$, in the particular representation specified, is immaterial.

Let (ξ_1, η_1, ζ_1), (ξ_2, η_2, ζ_2), (ξ_3, η_3, ζ_3) be taken as coördinates of three points P_1, P_2, P_3 in space, the origin of coördinates being designated by O. The expression $\sum (y_k - x_k)^2$ is equal to

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[1] A third important form of the theory is that in which the independent variable takes on an enumerable infinity of values; *cf.* E. Schmidt, Über die Auflösung linearer Gleichungen mit unendlich vielen Unbekannten, *Rendiconti del Circolo Matematico di Palermo*, vol. 25 (1908), pp. 53–77; see pp. 56–65.

[2] The denominators in the formulas for a_k, b_k, c_k are different from zero, because of the hypothesis of linear independence.

[3] That is, any sets, subject to (8), on which the x's, y's, and z's are linearly dependent.

$$\Sigma[(\xi_2 - \xi_1)a_k + (\eta_2 - \eta_1)b_k + (\zeta_2 - \zeta_1)c_k]^2$$
$$= (\xi_2 - \xi_1)^2\Sigma a_k^2 + (\eta_2 - \eta_1)^2\Sigma b_k^2 + (\zeta_2 - \zeta_1)^2\Sigma c_k^2$$
$$+ 2(\xi_2 - \xi_1)(\eta_2 - \eta_1)\Sigma a_k b_k + 2(\xi_2 - \xi_1)(\zeta_2 - \zeta_1)\Sigma a_k c_k$$
$$+ 2(\eta_2 - \eta_1)(\zeta_2 - \zeta_1)\Sigma b_k c_k$$
$$= (\xi_2 - \xi_1)^2 + (\eta_2 - \eta_1)^2 + (\zeta_2 - \zeta_1)^2,$$

and so is the square of the distance P_1P_2. The other distances in the figure can be calculated similarly. By the law of cosines in the triangle P_1OP_2 (or by a familiar formula of solid analytic geometry), the cosine of the angle $\theta = P_1OP_2$ is found to be

$$\cos\theta = \frac{\overline{OP_1}^2 + \overline{OP_2}^2 - \overline{P_1P_2}^2}{2\overline{OP_1}\cdot\overline{OP_2}} = \frac{\Sigma x_k^2 + \Sigma y_k^2 - \Sigma(y_k - x_k)^2}{2\sqrt{\Sigma x_k^2\Sigma y_k^2}}$$
$$= \frac{\Sigma x_k y_k}{\sqrt{\Sigma x_k^2\Sigma y_k^2}},$$

which, in the particular case that $\Sigma x_k = \Sigma y_k = 0$, is the coefficient of correlation of the sets of numbers $(x_1, \cdots, x_n)$, $(y_1, \cdots, y_n)$.

When distance and angle have been established, other geometrical measures can be worked out *ad libitum;* it would be superfluous to dwell on the details, beyond a reference to the discussion of the corresponding integral formulas in the preceding pages, and the paper T already cited. With the present definitions, a coefficient of partial correlation not merely resembles, but *is* the cosine of an angle between two planes, a coefficient of double correlation *is* the cosine of an angle between a line and a plane,[1] and, a little outside the ordinary notation of statistics, a Gramian determinant is found by actual calculation to be equal to the square of the volume of a parallelepiped. The geometrical basis of the statistical relations is thus concretely realized.

A RAPID METHOD OF APPROXIMATING ARITHMETIC ROOTS.

By GLENN JAMES, University of California, Southern Branch.

A method sometimes used to approximate the square root of a number consists of dividing the number by an estimated root and taking, for the root, the arithmetic mean between the divisor and the quotient,[2] for example,

$$\sqrt{6} = \tfrac{1}{2}(2.5 + 6/2.5) = 2.45.$$

This method is a special case of the following rule:

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[1] When the words *coefficient of correlation* are used, it is to be understood throughout that $\Sigma x_k = \Sigma y_k = \Sigma z_k = 0$; this means merely that the mathematical concepts are more general than is necessary for their immediate statistical application.

[2] See M. A. Nordgaard, "*A Historical Survey of Algebraic Methods of Approximating the Roots of Numerical Higher Equations,*" art. 3. New York, Columbia University, 1922.

RULE. *To extract the n-th integral root of a number divide an estimate of the root into the number, then into the quotient and so on until $n-1$ divisions have been made, and take for the root the arithmetic mean between the $n-1$ divisors and the final quotient; e.g.*

$$\sqrt[3]{20} = (3 + 3 + 20/9)/3 = 2.74.$$

Using the approximation to the root obtained in one step for the estimate in the next, one can repeat this process as many times as desired. Obviously the sequence of approximations thus obtained would converge to the desired root. However, the usefulness of such a method depends upon the establishment of measures of the errors in the successive approximations.

1. The Remainders in the Approximation of the nth Root of a Number.[1] Let E^n be the number whose nth root is to be extracted and let E_0 be the estimated root, and denote $E_0 - E$ by ϵ_0. Then

$$E^n = (E_0 - \epsilon_0)^n \tag{1}$$

and according to the rule the first approximation to the nth root of E^n would be

$$1/n[E^n/{E_0}^{n-1} + (n-1)E_0]. \tag{2}$$

By means of (1) this can be simplified into

$$E + \frac{(n-1){\epsilon_0}^2}{2E_0} - \frac{(n-1)(n-2){\epsilon_0}^3}{3!{E_0}^2} + \cdots. \tag{3}$$

The error in this approximation, namely,

$$\frac{(n-1){\epsilon_0}^2}{2E_0} - \frac{(n-1)(n-2){\epsilon_0}^3}{3!{E_0}^2} + \cdots \tag{4}$$

is positive for ϵ_0 is small relatively to E_0 and n. And, for ϵ_0 thus chosen the error in the ith approximation is less than

$$\frac{(n-1){\epsilon_{i-1}}^2}{2E_{i-1}}, \qquad i > 1, \tag{5}$$

where ϵ_{i-1} and E_{i-1}, respectively, denote the error and the approximated root of the previous step. Moreover, when ϵ_0 is negative and small relatively to n and E_0, the second term of (4) is small relatively to the first. Besides, we are not so much interested in the first digit in the error as we are in its position relative to the decimal point. In the light of these considerations we are justified in determining the measure of the errors from the sequence,

$$\epsilon_0, \epsilon_1', \epsilon_2', \epsilon_3', \cdots, \tag{6}$$

[1] This paper considers only numbers greater than unity since the application of its result to fractions requires only the proper placing of the decimal point in the roots.

where

$$\epsilon_1' = \frac{(n-1)\epsilon_0^2}{2E_0}, \tag{7}$$

$$\epsilon_2' = \frac{(n-1)(\epsilon_1')^2}{2E_1} = \frac{(n-1)^3\epsilon_0^4}{2^3E_0^2E_1}, \tag{8}$$

$$\epsilon_3' = \frac{(n-1)(\epsilon_2')^2}{2E_2} = \frac{(n-1)^7\epsilon_0^8}{2^7E_0^4E_1^2E_2}, \tag{9}$$

and in general

$$\epsilon_i' = \frac{(n-1)^{2^{i-1}}\epsilon_0^{2^i}}{2^{2^{i-1}}E_0^{2^{i-1}}E_1^{2^{i-2}}\cdots E_{i-1}}. \tag{10}$$

But

$$E_j \equiv E_{j-1}, \qquad j = 2, 3, \cdots, i, \tag{11}$$

for

$$E_j = \frac{1}{n}\left[(n-1)E_{j-1} + \frac{E^n}{{E_{j-1}}^{n-1}}\right]$$

$$= \frac{n{E_{j-1}}^n + E^n - {E_{j-1}}^n}{n{E_{j-1}}^{n-1}},$$

which is equal to or less than E_{j-1} provided $E_{j-1} \geqq E$, and this is true whenever $j > 1$. Moreover, E_0 will differ from E_{i-1} by an additive error which is small relatively to E_0. Hence we shall use for our measure of error in the ith approximation, M_i, where

$$M_i = \frac{(n-1)^{2^i-1}\epsilon_0^{2^i}}{2^{2^i-1}{E_{i-1}}^{2^i-1}}.$$

This can be written in the form

$$M_i = \left[\frac{(n-1)\epsilon_0}{2E_{i-1}}\right]^{2^i-1}\epsilon_0. \tag{12}$$

It remains now to indicate rules for making estimates of roots, which will assure certain upper limits for ϵ_0. These upper limits should be as small as possible without requiring more labor to make the estimates than would be required to secure as small errors from easier estimates by additional approximations.

For any value of n, ϵ_0 can be made less than .5 by choosing for E_0 the arithmetic mean between the two integers nearest the correct root. For example, if the estimated fifth root of any number between 1 and 32 be 1.5, neither it nor any of the sequence of approximations could differ from the correct root by more than .5.

Whence we have for the measure of the error in the ith approximation to the nth root,

$$M_i = \frac{1}{2}\left[\frac{n-1}{4E_{i-1}}\right]^{2^i-1}. \tag{13}$$

For $n = 2$ and $n = 3$, it is worth while to indicate rules which give smaller upper limits for the errors.

2. Limits of Error in Estimated Square and Cube Roots. It should be noted first that for the square root

$$\epsilon_1 = \epsilon_0^2/2E_0,$$

$$\epsilon_2 = \epsilon_1^2/2E_1,$$

and in general

$$\epsilon_i = \epsilon_{i-1}^2/2E_{i-1}. \tag{14}$$

Now, two successive squares bound an even number of integers and the square of the arithmetic mean between the roots of two successive squares divides these integers into equal sets. That is,

$$a^2 + a < (a + \tfrac{1}{2})^2 < a^2 + 2a.$$

From this consideration it follows that *the error in an estimated square root of an integer will be less than* $\frac{1}{2}$ *if we choose for the estimate the square root of the next lesser or next greater square according to which the given integer is nearer; and the error will be less than* $\frac{1}{4}$ *if we make these estimates respectively* $\frac{1}{4}$ *larger and* $\frac{1}{4}$ *smaller.* For example, if 1 be the estimated root of 2, the error is less than .5, while if 1.25 be the estimated root, the error is less than .25. If the number be not an integer, we obtain the same limits for the errors if we make the above estimates *according as the number is less than or greater than the square of the arithmetic mean between the roots of the nearest squares.*

For the cube root,

$$M_i = \left[\frac{\epsilon_0}{E_{i-1}}\right]^{2^{i-1}} \epsilon_0 \tag{15}$$

and ϵ_0 can be made less than $\frac{1}{3}$ as we shall now show.

The number of integers between a^3 and $(a + 1)^3$ is divisible by three. Consider them divided into three equal sets; first, all that are less than $a^3 + a^2 + a + 1$; second, all that are equal to or greater than $a^3 + a^2 + a + 1$ and less than $a^3 + 2a^2 + 2a + 1$; and third, all that are equal to or greater than $a^3 + 2a^2 + 2a + 1$. *Now, if we choose for the estimated cube root of a given number* $a + \frac{1}{3}$, $a + \frac{2}{3}$ *or* $a + 1$, *according as the number is in the first, second, or third set, the error will be less than* $\frac{1}{3}$, *because for* $a \gtreqless 1$,

$$(a + \tfrac{1}{3})^3 < a^3 + a^2 + a + 1,$$

$$a^3 + a^2 + a + 1 < (a + \tfrac{2}{3})^3 < a^2 + 2a^2 + 2a + 1,$$

and

$$a^2 + 2a^2 + 2a + 1 < (a + 1)^3.$$

Hence there could not be an error of $\frac{1}{3}$ in such an estimate without contradicting the fact that the number is in the given set.

3. Illustrative Example. To evaluate $\sqrt[3]{52.75}$, choose 4 for the estimated cube root.

Then

$$E_1 = \left(\frac{52.75}{16} + 8\right)\Big/3 = 3.7448.$$

$$M_1 = .028 -.$$

$$E_2 = \left(\frac{52.75}{3.75^2} + 7.5\right)\Big/3 = 3.75106 -.$$

$$M_2 = .0003 -.$$

$$E_3 = 3.7510770 +.$$

$$M_3 = .000{,}000{,}02 -.$$

A SIMPLE DISCUSSION OF THE REPRESENTATION OF FUNCTIONS BY FOURIER SERIES.

By PHILIP FRANKLIN, Massachusetts Institute of Technology.

1. Introduction. Some time ago Professor Birkhoff (*1921*, 200) gave a brief treatment of the Fourier expansion of functions which were periodic and had three continuous derivatives. As most of the elementary examples of Fourier expansions correspond to functions with discontinuities, at least at the end points of the fundamental period interval, it is thought that the following discussion, which covers such cases, may be of interest. While our proof reduces everything to first principles, it is much briefer than those usually given.

2. Theorem. Having defined the Fourier coefficients of a function $f(x)$ by the equations

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\cos ntdt; \qquad b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\sin ntdt,$$

we shall now establish the following theorem:

THEOREM. *Let $f(x)$ be a periodic function, period 2π, continuous with a continuous first derivative, except for a finite number of points in each period interval, and let it have forward and backward derivatives at the points of discontinuity. Moreover, let it be defined as equal to the average value of its right and left hand limit values at those points. Then $f(x)$ is represented by the series*

$$\tfrac{1}{2}a_0 + \sum_{n=1}^{\infty}(a_n \cos nx + b_n \sin nx).$$

PROOF. We wish to prove that

$$f(x) = \lim_{n=\infty} S_n,$$

where

$$S_n = \frac{1}{2}a_0 + \sum_{m=1}^{n} (a_m \cos mx + b_m \sin mx)$$

$$= \frac{1}{2\pi}\int_{-\pi}^{\pi} f(t)dt + \sum_{m=1}^{n}\left(\frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\cos mtdt \cos mx + \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\sin mtdt \sin mx\right)$$

$$= \frac{1}{\pi}\int_{-\pi}^{\pi} f(t)\left[\frac{1}{2} + \sum_{m=1}^{n}\cos m(t-x)\right]dt.$$

We first change the variable of integration from t to u where

$$t = u + x.$$

Since the integrand is periodic, we may integrate over any complete period, and hence keep the limits unchanged, obtaining

$$S_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(u+x)\left[\frac{1}{2} + \sum_{m=1}^{n}\cos mu\right]du = \frac{1}{\pi}\int_{-\pi}^{\pi} f(u+x)s_n du.$$

We may evaluate the trigonometric sum s_n by the following device:

$$(2\sin u/2)s_n = \sin u/2 + \sum_{m=1}^{n} 2\cos mu \sin u/2$$

$$= \sin u/2 + \sum_{m=1}^{n}[\sin(m+\tfrac{1}{2})u - \sin(m-\tfrac{1}{2})u]$$

$$= \sin(n+\tfrac{1}{2})u,$$

since the remaining terms appear twice with opposite signs. This gives:

$$s_n = \frac{1}{2} + \sum_{m=1}^{n}\cos mu = \frac{\sin(n+\frac{1}{2})u}{2\sin u/2}.$$

Our problem now is to show that

$$f(x) = \lim_{n=\infty}\frac{1}{\pi}\int_{-\pi}^{\pi} f(u+x)s_n du.$$

From the definition of $f(x)$ at the points of discontinuity, at all points,

$$f(x) = \tfrac{1}{2}f(x+) + \tfrac{1}{2}f(x-).$$

Since

$$\frac{1}{\pi}\int_{-\pi}^{\pi} f(u+x)s_n du = \frac{1}{\pi}\int_{0}^{\pi} f(u+x)s_n du + \frac{1}{\pi}\int_{-\pi}^{0} f(u+x)s_n du,$$

the conclusion will follow if

$$\frac{1}{2}f(x+) = \lim_{n=\infty}\frac{1}{\pi}\int_{0}^{\pi} f(u+x)s_n du; \quad \text{and} \quad \frac{1}{2}f(x-) = \lim_{n=\infty}\frac{1}{\pi}\int_{-\pi}^{0} f(u+x)s_n du.$$

We shall merely prove the first in full, as the second can be proved either by similar reasoning, or by applying the first result to the function $F(y) = f(2x - y)$.

Since

$$\frac{1}{\pi}\int_0^\pi s_n du = \frac{1}{\pi}\int_0^\pi \left[\frac{1}{2} + \sum_{m=1}^{n} \cos mu\right] du = \frac{1}{2},$$

$$\frac{1}{2} f(x+) = \frac{1}{\pi}\int_0^\pi f(x+)s_n du = \lim_{n=\infty} \frac{1}{\pi}\int_0^\pi f(x+)s_n du.$$

Thus the equation in question will follow from

$$\lim_{n=\infty} \frac{1}{\pi}\int_0^\pi f(x+)s_n du = \lim_{n=\infty} \frac{1}{\pi}\int_0^\pi f(u+x)s_n du,$$

or

$$\lim_{n=\infty} \int_0^\pi [f(u+x) - f(x+)]s_n du = 0.$$

To discuss this equation, we break up the interval of integration $(0, \pi)$ into smaller intervals: $(0, p_0)$, (p_0, p_1), $\cdots$, (p_{D-1}, π); where $p_1, \cdots, p_{D-1}$ are the values of u for which $f(u+x)$ is discontinuous (exclusive of 0, which may be such a value), and where p_0 is a value between 0 and p_1 to be specified presently.

The integral in the first interval is:

$$\int_0^{p_0} [f(u+x) - f(x+)]s_n du = \int_0^{p_0} \frac{f(u+x) - f(x+)}{u} \cdot \frac{u/2}{\sin u/2} \sin\left(n + \frac{1}{2}\right)u du,$$

as appears upon replacing s_n by its value, and inserting the factor u in both numerator and denominator. We may now obtain upper bounds for each factor in succession. Thus,

$$\left|\frac{f(x+u) - f(x+)}{u}\right| = f'(x + \theta u) \leq D, \qquad (|\theta| < 1),$$

as appears upon using the law of the mean, letting D represent an upper bound for the derivative of the given function $f(x)$. Moreover,

$$\frac{u/2}{\sin u/2} \leq \frac{\pi}{2},$$

since its derivative $\dfrac{(\cos u/2)(\tan u/2 - u/2)}{2 \sin^2 u/2}$ is positive in the interval $(0, \pi)$, showing that its maximum value in that interval is that for $u = \pi$, or $\pi/2$.

Finally,

$$|\sin (n + \tfrac{1}{2})u| \leq 1.$$

Consequently,

$$\left|\int_0^{p_0} [f(u+x) - f(x+)]s_n du\right| \leq \left|\int_0^{p_0} D \cdot \frac{\pi}{2} \cdot 1 du\right| \leq \frac{D\pi p_0}{2}.$$

This can be made small, say less than $\epsilon/2$, by taking p_0 small.

The remaining integrals may now be treated by integrating by parts. We have:

$$I_k = \int_{p_{k-1}}^{p_k} [f(u+x) - f(x+)]s_n du$$

$$= \int_{p_{k-1}}^{p_k} \frac{f(u+x) - f(x+)}{2 \sin u/2} \sin\left(n + \frac{1}{2}\right) u du$$

$$= -\frac{f(u+x) - f(x+)}{2 \sin u/2} \frac{\cos (n+\frac{1}{2})u}{n+\frac{1}{2}} \Bigg|_{p_{k-1}}^{p_k}$$

$$+ \frac{1}{n+\frac{1}{2}} \int_{p_{k-1}}^{p_k} \left[\frac{f'(u+x) \cos (n+\frac{1}{2})u}{2 \sin u/2} \right.$$

$$\left. - \frac{[f(u+x) - f(x+)] \cos (n+\frac{1}{2})u \cos u/2}{4 \sin^2 u/2} \right] du.$$

But, if F is an upper bound for $f(x)$,

$$|f(u+x) - f(x+)| \leq 2F,$$

while, since all the p_i are greater than p_0,

$$\sin u/2 > \sin p_0/2.$$

It follows from these inequalities that

$$|I_k| \leq \frac{1}{n+\frac{1}{2}} \left[\frac{2F}{\sin p_0/2} + (p_{k+1} - p_k) \left(\frac{D}{2 \sin p_0/2} + \frac{F}{2 \sin^2 p_0/2} \right) \right].$$

As the quantity in the braces is independent of n, the sum of all the integrals I_k will be numerically less than some expression independent of n (though involving ϵ through p_0), divided by $n + \frac{1}{2}$. Consequently, by taking n sufficiently large ($\geq N$), it can be made small, say less than $\epsilon/2$.

We have shown that, for any ϵ, an n can be found for which

$$\int_0^\pi [f(u+x) - f(x+)]s_n du < \epsilon \qquad \text{if} \qquad n \geq N.$$

Consequently, when $n = \infty$, the limit of the left member must be zero, thus completing the proof.

AN ELEMENTARY ANALYSIS OF THE GENERAL EQUATION OF SECOND DEGREE.[1]

By E. S. ALLEN, Iowa State College.

1. Introduction. Almost all elementary books on analytic geometry analyze the general quadratic equation in x and y by means of two changes of axes. It is, so far as I know, only in Smith's *Conic Sections* (p. 207) that a method of finding the foci of a conic section without change of coördinates is described. This method makes use of the polar properties of the foci and directrices. While making a class acquainted with conics recently, I was asked how it was possible to find the eccentricity, directrices, and foci of such a curve directly from its equation. The following answer to the question, which uses only "elementary" mathematical ideas, is, I believe, new.

2. General considerations. If a conic has the focus (α, β), the directrix

$$x \cos\theta + y \sin\theta - p = 0$$

and the eccentricity e, its equation is

$$\sqrt{(x-\alpha)^2 + (y-\beta)^2} = e(x\cos\theta + y\sin\theta - p);$$

that is,

$$\begin{aligned} &x^2(1 - e^2\cos^2\theta) - 2xy(e^2\sin\theta\cos\theta) + y^2(1 - e^2\sin^2\theta) \\ &\quad - 2x(\alpha - e^2p\cos\theta) - 2y(\beta - e^2p\sin\theta) + (\alpha^2 + \beta^2 - e^2p^2) = 0. \end{aligned} \tag{1}$$

In order that the equation

$$ax^2 + 2hxy + by^2 + 2gx + 2fy + c = 0 \tag{2}$$

may have the same coefficients as an equation of the form (1), it is necessary that

$$(a-1)(b-1) = h^2.$$

This results from the first three of the following equations:

$$\begin{aligned} a &= 1 - e^2\cos^2\theta, & g &= -(\alpha - e^2p\cos\theta), \\ h &= -e^2\sin\theta\cos\theta, & f &= -(\beta - e^2p\sin\theta), \\ b &= 1 - e^2\sin^2\theta, & c &= \alpha^2 + \beta^2 - e^2p^2. \end{aligned} \tag{3}$$

Consequently, if we have any equation of second degree, with real coefficients,

$$a'x^2 + 2h'xy + b'y^2 + 2g'x + 2f'y + c' = 0, \tag{4}$$

we must multiply the first member by such a number k that

$$(ka' - 1)(kb' - 1) = (kh')^2. \tag{5}$$

[1] Read at the meeting of the Iowa Section of the Mathematical Association of America, May 2, 1924.

3. Parabola. In the case of the parabola, $a'b' - h'^2 = 0$, equation (5) is linear, and the values of $a, b, \cdots, c$ are uniquely determined. If we demand that $0 \leqq \theta < \pi$, all the numbers $e, \alpha, \beta, \theta, p$ are found without ambiguity.

4. Central conic. If we have a central conic, then $a'b' - h'^2 \neq 0$, and the roots of (5) are

$$k_1 = \frac{(a' + b') + \sqrt{(a' + b')^2 - 4(a'b' - h'^2)}}{2(a'b' - h'^2)},$$
$$k_2 = \frac{(a' + b') - \sqrt{(a' + b')^2 - 4(a'b' - h'^2)}}{2(a'b' - h'^2)}. \tag{6}$$

Thus, k_1 and k_2 are evidently real.

It follows from (3) that

$$e^2 = 2 - (a + b) = 2 - k(a' + b')$$
$$= \frac{-(a' + b')^2 + 4(a'b' - h'^2) \mp (a' + b')\sqrt{(a' + b')^2 - 4(a'b' - h'^2)}}{2(a'b' - h'^2)}. \tag{7}$$

5. Ellipse. In the case of the ellipse (where $a'b' - h'^2 > 0$) the absolute value of the last term of the numerator is greater than that of the other two. Accordingly, one value of e is real, the other imaginary. To obtain the real foci and directrices of a real ellipse, it is necessary to take the last term of (7) positive.

From the known values of a, h, b, that of θ is then determined. Equations (3) for g, f, c give us a quadratic equation for the determination of p; its roots are the values of p for the two real directrices. The values of α and β are then found immediately.

6. Hyperbola. If $a'b' - h'^2 < 0$, the curve is a hyperbola. Equation (7) shows that e^2 is necessarily positive; for the absolute value of the last term of the numerator is in this case less than that of the other terms. The latter are negative, as is the denominator. That eccentricity which corresponds to the real foci has, then, to be chosen. Having e, we are now able to find p.

The equation which p must satisfy is

$$(e^4 - e^2)p^2 - 2e^2(g \cos\theta + f \sin\theta)p + g^2 + f^2 - c = 0.$$

The quotient of the discriminant of this equation by the positive number e^2 is

$$B = g^2(1 - a) - 2fgh + f^2(1 - b) - (e^2 - 1)(g^2 + f^2 - c)$$
$$= bg^2 - 2fgh + af^2 + c(1 - a - b)$$
$$= k^3(b'g'^2 - 2f'g'h' + a'f'^2) - k^2c'(a' + b') + kc'.$$

Now, from (5),

$$k(a' + b') - 1 = k^2(a'b' - h'^2);$$

consequently

$$B = -k^3 \begin{vmatrix} a' & h' & g' \\ h' & b' & f' \\ g' & f' & c' \end{vmatrix}.$$

In view of the fact that $k_1 k_2 = \dfrac{1}{a'b' - h'^2} < 0$, the two values of B will have opposite signs, and that one of the two k's must be chosen whose sign is opposite that of the determinant. k having been found, the solution is identical with that for the ellipse.

7. Perpendicularity of axes. Since

$$\tan\theta_1 \tan\theta_2 = \frac{k_1 h'}{k_1 a' - 1} \cdot \frac{k_2 h'}{k_2 a' - 1} = \frac{\dfrac{h'^2}{a'b' - h'^2}}{\dfrac{a'^2}{a'b' - h'^2} - \dfrac{(a' + b')a'}{a'b' - h'^2} + 1} = -1,$$

we find, of course, that the two values of θ differ by $\dfrac{\pi}{2}$.

QUESTIONS AND DISCUSSIONS.

EDITED BY C. F. GUMMER, Queen's University, Kingston, Ont., Canada.

The department of Questions and Discussions in the MONTHLY is open to all forms of activity in collegiate mathematics, including the teaching of mathematics, except for specific problems, especially new problems, which are reserved for the separate department of Problems and Solutions.

DISCUSSIONS.

I. ON CHECKING THE SOLUTION OF A TRIANGLE.

BY C. N. MILLS, Teachers College, Aberdeen, S. Dak.

In the June, 1924, issue of the MONTHLY, page 292, Professor E. J. Moulton gives a discussion relative to using the Sine Theorem for checking the solution of a triangle. For a complete and dependable check it is much better to use a formula which involves all the sides and angles of the triangle. Besides the usual relation that the sum of the angles must equal 180°, use the formula

$$(a - b)\cos(C/2) = c \sin[(A - B)/2].$$

When using logarithms the products are readily found, since the logarithms of some of the terms have been used in finding the required parts.

This equation is known as Mollweide's equation, but it was known before his time. (See Wilczynski, *Plane Trigonometry and Applications*, pages 104 and 105.)

II. On Taking Square Roots of Integers.

By D. F. Barrow, University of Georgia.

The Diophantine equation

$$y^2 - nx^2 = 1 \tag{1}$$

has integral solutions in x and y when n is not a perfect square and they have the following property:[1] If x_0 and y_0 satisfy (1), then

$$\begin{aligned} x_1 &= 2x_0y_0, \\ y_1 &= 2y_0^2 - 1 \end{aligned} \tag{2}$$

will also satisfy (1).[2]

Now it is evident that if x and y are large numbers satisfying (1), the fraction y/x will be a close approximation to the square root of n. Furthermore, if we can find any solution of (1), then successive applications of (2) will give us as large a solution as we please. We can thus find the square root of n as accurately as we please as a common fraction; and, of course, reduce it to a decimal if we wish. The method seems to be of most use in case very accurate results are desired.

As an example we will find the square root of 2 to fifty decimals. By inspecting the equation

$$y^2 - 2x^2 = 1,$$

we see that $x_0 = 2$ and $y_0 = 3$ furnish an initial solution. Then, by successive applications of (2), we find:

$$\begin{aligned} x_1 &= 2\cdot2\cdot3 & y_1 &= 17 \\ x_2 &= 2\cdot2\cdot2\cdot3\cdot17 & y_2 &= 577 \\ x_3 &= 2\cdot2\cdot2\cdot2\cdot3\cdot17\cdot577 & y_3 &= 665857 \\ x_4 &= 2\cdot2\cdot2\cdot2\cdot2\cdot3\cdot17\cdot577\cdot665857 & y_4 &= 866731088897. \end{aligned}$$

If we divide the largest value of y by the corresponding value of x, we obtain the square root of two to about twenty-four decimals. However, the following method, which is evidently applicable to all such problems, is more convenient and increases the accuracy without using any larger numbers: From (2) we find

$$y_1/x_1 = y_0/x_0 - 1/2x_0y_0. \tag{3}$$

Now we will use subscripts to denote the successive values of x and y obtained from an initial pair of values by use of (2); and remember that the accuracy increases with the size of the numbers. We are led to the following series:

$$\sqrt{n} = y_0/x_0 - 1/2x_0y_0 - 1/4x_0y_0y_1 - 1/8x_0y_0y_1y_2 - \cdots. \tag{4}$$

[1] R. D. Carmichael, *Diophantine Analysis*, pp. 26–29. John Wiley & Sons.

[2] This fact was noted by Wallis. See L. E. Dickson, *History of the Theory of Numbers*, vol. 2, p. 351. Editor.

Each term of this series is obtained from the preceding by dividing by twice the appropriate value of y. In the following calculation the successive terms of this series are shown for the example we took where $n = 2$. It was found that six terms gave forty-eight decimals accurately, and so the first few digits of the seventh were calculated by logarithms. A check calculation was carried out starting with the numbers $x_0 = 70$ and $y_0 = 99$, and the result agreed with that given below. Thus the square root of two is checked through the fifty-third decimal place.

It looks as if the success of this method depended on the accidental discovery of some solution of (1) to start with. The following numerical example will illustrate a general method which is straightforward and always certain of success.

To find a positive integral solution of

$$y^2 - 13x^2 = 1.$$

Suppose (x, y) to be a solution.[1] Evidently y is greater than $3x$ and less than $4x$. Set $y = 3x + y'$ and obtain

$$y'^2 + 6xy' - 4x^2 = 1.$$

Evidently x is greater than y' but less than $2y'$. So we set $x = y' + x'$ and obtain

$$3y'^2 - 2x'y' - 4x'^2 = 1.$$

Now the idea is that these substitutions give us equations satisfied by smaller and smaller numbers, and we must finally reach an equation whose solution is (0, 1) or else (1, 1). When this happens we will see it by inspection, and can then trace back through the successive substitutions to the values that satisfy the initial equation. In the case we are solving, we are led through the additional substitutions:

$$y' = x' + y'', \quad x' = y'' + x'', \quad y'' = x'' + y''', \quad x'' = 6y''' + x''',$$
$$y''' = x''' + y^{iv}, \quad x''' = y^{iv} + x^{iv}, \quad y^{iv} = x^{iv} + y^{v},$$

to the final equation

$$3y^{v2} + 2x^{iv}y^{v} - 4x^{iv2} = 1;$$

and this is satisfied by (1, 1). Tracing back to the beginning, we find that $x = 180$ and $y = 649$ is the solution of the equation we started with.

The details of the calculation of square root of two by the series

$$\sqrt{2} = 3/2 - 1/2\cdot2\cdot3 - 1/2\cdot2\cdot2\cdot3\cdot17 - \cdots$$

[1] The argument used here does not include a proof of the existence of a solution. That a solution exists was first proved by Lagrange (see Dickson, *History*, vol. 2, p. 358). Lagrange's treatment may be found in G. Chrystal, *Textbook of Algebra*, part 2 (1900), pp. 478–481. For a different treatment, see R. D. Carmichael, *Diophantine Analysis*. EDITOR.

are as follows:

1.50000 00000 00000 00000 00000 00000 00000 00000 00000 00000 0000
−.08333 33333 33333 33333 33333 33333 33333 33333 33333 33333 3333
−.00245 09803 92156 86274 50980 39215 68627 45098 03921 56862 7450
−.00000 21238 99819 89329 52730 48560 84548 20430 03122 98229 5171
−.00000 00000 01594 86182 46059 55387 60466 65015 77696 33954 6616
−.00000 00000 00000 00000 00008 99292 83216 50453 10050 39896 3426
−.00000 00000 00000 00000 00000 00000 00000 00000 00000 00028 5928.

When the negative terms are added together and subtracted from the positive term, the following value is obtained for the square root of two:

1.41421 35623 73095 04880 16887 24209 69807 85696 71875 37694 807 ⋯.

III. Real Roots of Equations with Complex Coefficients.

By I. A. Barnett, University of Cincinnati.

The purpose of this note is to give necessary and sufficient conditions that algebraic equations of the second and third degrees with complex coefficients shall have an assigned number of real roots. These criteria follow almost immediately as corollaries of a theorem given in Dickson's *Elementary Theory of Equations*, First Edition, page 164. This theorem is as follows:

Necessary and sufficient conditions that

$$f(x) = a_0x^m + a_1x^{m-1} + \cdots + a_m, \qquad a_0 \neq 0,$$

and

$$g(x) = b_0x^n + b_1x^{n-1} + \cdots + b_n, \qquad b_0 \neq 0,$$

shall have a common divisor of degree d, but none of higher degree, are $R = 0$, $R_1 = 0, \cdots, R_{d-1} = 0, R_d \neq 0$, where R is given by the expression

$$R = \begin{vmatrix}
a_0 & a_1 & a_2 & \cdots & a_m & 0 & & \cdots & & 0 \\
0 & a_0 & a_1 & a_2 & \cdots & a_m & 0 & \cdots & & 0 \\
0 & 0 & a_0 & a_1 & a_2 & \cdots & a_m & 0 & \cdots & 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
0 & & \cdots & 0 & a_0 & a_1 & a_2 & \cdots & & a_m \\
b_0 & b_1 & & \cdots & & b_n & 0 & \cdots & & 0 \\
0 & b_0 & b_1 & & \cdots & & b_n & \cdots & & 0 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
0 & \cdots & 0 & b_0 & b_1 & & & \cdots & & b_n
\end{vmatrix}$$

(n rows; m rows)

and R_k is the determinant derived from R by deleting the last k rows of a's, the last k rows of b's, and the last $2k$ columns.

This will be referred to as Theorem A.

In case $m = n$, one may write the determinant R in the form

$$R = (-1)^{[n(n-1)]/2} \begin{vmatrix} d_{11} & \cdots & d_{1n} \\ d_{21} & \cdots & d_{2n} \\ \vdots & & \\ d_{n1} & \cdots & d_{nn} \end{vmatrix},$$

where

$$d_{ij} = (a_0 b_{i+j-1}) + (a_1 b_{i+j-2}) + \cdots + (a_{i-1} b_j)$$

and

$$(a_i b_k) = a_i b_k - a_k b_i.$$

1. Consider first the quadratic equation

$$ax^2 + bx + c = 0, \qquad a \neq 0, \tag{1}$$

where

$$a = \alpha_1 + i\alpha_2, \qquad b = \beta_1 + i\beta_2, \qquad c = \gamma_1 + i\gamma_2.$$

Equation (1) may be written in the form

$$\alpha_1 x^2 + \beta_1 x + \gamma_1 + i(\alpha_2 x^2 + \beta_2 x + \gamma_2) = 0. \tag{2}$$

Case 1. One and only one real root. Suppose it is required that (1) shall have one and only one real root x_1. From (2) it is seen that a necessary and sufficient condition for this to be so is that the equations

$$\alpha_1 x^2 + \beta_1 x + \gamma_1 = 0 \tag{3}$$

and

$$\alpha_2 x^2 + \beta_2 x + \gamma_2 = 0 \tag{4}$$

shall have one and only one real root x_1 in common. In other words, the left hand members of (3) and (4) must have a linear factor in common and no factor of higher degree. Therefore, upon application of Theorem A, one may state the following result:

Necessary and sufficient conditions that equation (1) *have one and only one real root are that*

$$Q_1 = \begin{vmatrix} \alpha_1 & \beta_1 & \gamma_1 & 0 \\ 0 & \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 & 0 \\ 0 & \alpha_2 & \beta_2 & \gamma_2 \end{vmatrix} = 0, \qquad Q_2 = \begin{vmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{vmatrix} \neq 0,$$

which may also be written in the form

$$Q_1 \equiv (\alpha_1\gamma_2)^2 - (\alpha_1\beta_2)(\beta_1\gamma_2) = 0, \qquad Q_2 \equiv (\alpha_1\beta_2) \neq 0.$$

That is, $(\alpha_1\gamma_2)$ is a mean proportional between $(\alpha_1\beta_2)$ and $(\beta_1\gamma_2)$.

It follows of course as a corollary that $Q_1 \neq 0$ is a necessary and sufficient condition that the quadratic equation (1) have no real root.

Another corollary is that a quadratic equation with real coefficients ($\alpha_2 = \beta_2 = \gamma_2 = 0$) cannot have one real root.

Case 2. Two real roots. Let it now be required that both roots of (1) be real. Then (3) and (4) must have two real roots in common. Now, according to Theorem A, $Q_1 = 0$, $Q_2 = 0$ would be necessary and sufficient conditions that the left hand members of (3) and (4) have a quadratic factor in common, but this would be the case even if equations (3) and (4) had a complex root in common. To rule out this case one must have the condition $\beta_1^2 - 4\alpha_1\gamma_1 \geqq 0$. Hence, necessary and sufficient conditions that equation (1) have two real roots are:

$$Q_1 = 0, \qquad Q_2 = 0, \qquad \beta_1^2 - 4\alpha_1\gamma_1 \geqq 0.$$

This may be put more simply. For, the condition $Q_2 \equiv (\alpha_1\beta_2) = 0$ with $Q_1 = 0$ implies $(\alpha_1\gamma_2) = 0$; and hence,

$$\alpha_2 = \rho\alpha_1, \qquad \beta_2 = \rho\beta_1, \qquad \gamma_2 = \rho\gamma_1.$$

Thus equation (1) reduces to

$$\alpha_1 x^2 + \beta_1 x + \gamma_1 = 0$$

with the restriction $\beta_1^2 - 4\alpha_1\gamma_1 \geqq 0$, as was to be expected.

One may note in passing that when the two roots of equation (1) are equal but not necessarily real, one must have the two conditions

$$\begin{cases} \beta_1^2 - \beta_2^2 - 4\alpha_1\gamma_1 + 4\alpha_2\gamma_2 = 0 \\ \beta_1\beta_2 - 2\alpha_1\gamma_2 - 2\alpha_2\gamma_1 = 0 \end{cases}$$

obtained by setting the discriminant of (1) equal to zero.

2. Consider next the cubic equation

$$ax^3 + bx^2 + cx + d = 0, \qquad a \neq 0, \tag{5}$$

which may be written more explicitly

$$(\alpha_1 x^3 + \beta_1 x^2 + \gamma_1 x + \delta_1) + i(\alpha_2 x^3 + \beta_2 x^2 + \gamma_2 x + \delta_2) = 0.$$

Case 1. One and only one real root. The equations

$$\alpha_1 x^3 + \beta_1 x^2 + \gamma_1 x + \delta_1 = 0, \tag{6}$$

$$\alpha_2 x^3 + \beta_2 x^2 + \gamma_2 x + \delta_2 = 0 \tag{7}$$

must have one and only one real root in common. Hence, by Theorem A, one has that necessary and sufficient conditions that equation (5) has one and only one real root are that

$$C_1 \equiv \begin{vmatrix} \alpha_1 & \beta_1 & \gamma_1 & \delta_1 & 0 & 0 \\ 0 & \alpha_1 & \beta_1 & \gamma_1 & \delta_1 & 0 \\ 0 & 0 & \alpha_1 & \beta_1 & \gamma_1 & \delta_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \delta_2 & 0 & 0 \\ 0 & \alpha_2 & \beta_2 & \gamma_2 & \delta_2 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 & \gamma_2 & \delta_2 \end{vmatrix} = 0, \qquad C_2 = \begin{vmatrix} \alpha_1 & \beta_1 & \gamma_1 & \delta_1 \\ 0 & \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \delta_2 \\ 0 & \alpha_2 & \beta_2 & \gamma_2 \end{vmatrix} \neq 0.$$

The expansions of these determinants may be put in the following form (cf. Dickson's Theory of Equations, p. 156):

$$C_1 \equiv (\alpha_1\delta_2)^3 - 2(\alpha_1\beta_2)(\alpha_1\delta_2)(\gamma_1\delta_2) - (\alpha_1\gamma_2)(\alpha_1\delta_2)(\beta_1\delta_2) + (\alpha_1\gamma_2)^2(\gamma_1\delta_2) + (\alpha_1\beta_2)(\beta_1\delta_2)^2 - (\alpha_1\beta_2)(\beta_1\gamma_2)(\gamma_1\delta_2),$$

$$C_2 \equiv (\alpha_1\gamma_2)^2 - (\alpha_1\beta_2)[(\beta_1\gamma_2) + (\alpha_1\delta_2)].$$

Case 2. Two and only two real roots. The left hand members of (6) and (7) must now have a quadratic factor in common but since it is further required that the common roots be real, one must have, moreover, that the discriminant of (6) be non-negative. Hence *necessary and sufficient conditions that equation* (5) *shall have two and only two real roots are that*

$$C_1 = 0, \qquad C_2 = 0, \qquad C_3 \equiv \begin{vmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{vmatrix} \neq 0,$$

and

$$\Delta \equiv 18\alpha_1\beta_1\gamma_1\delta_1 - 4\beta_1^3\delta_1 + \beta_1^2\gamma_1 - 4\alpha_1\gamma_1^3 - 27\alpha_1^2\delta_1^2 \geqq 0.$$

One may readily verify that the conditions $C_1 = 0$, $C_2 = 0$ may be replaced by the simpler conditions

$$C_2 = 0, \qquad (\alpha_1\delta_2)^3 - (\alpha_1\beta_2)(\alpha_1\delta_2)(\gamma_1\delta_2) - (\alpha_1\gamma_2)(\alpha_1\delta_2)(\beta_1\delta_2) + (\alpha_1\beta_2)(\beta_1\delta_2)^2 = 0.$$

Case 3. Three real roots. Applying Theorem A, one finds immediately that *necessary and sufficient conditions for equation* (5) *to have three real roots are that*

$$C_1 = 0, \qquad C_2 = 0, \qquad C_3 = 0, \qquad \Delta \geqq 0.$$

Since $C_3 \equiv (\alpha_1\beta_2) = 0$, one sees from the expanded form of C_2 that $(\alpha_1\gamma_2) = 0$, and hence, from the expression for C_1, that $(\alpha_1\delta_2) = 0$. Hence,

$$\alpha_2 = \rho\alpha_1, \qquad \beta_2 = \rho\beta_1, \qquad \gamma_2 = \rho\gamma_1, \qquad \delta_2 = \rho\delta_1,$$

and equation (5) reduces to

$$\alpha_1x^3 + \beta_1x^2 + \gamma_1x + \delta_1 = 0$$

with the condition $\Delta \geqq 0$.

RECENT PUBLICATIONS.

EDITED BY W. B. CARVER, Cornell University, to whom books and communications should be sent.

REVIEWS.

Projective Geometry. By R. M. WINGER. New York, D. C. Heath and Co., 1923. xiii + 443 pages. Price, $4.40.

The task which Professor Winger has set himself in this book and the notable contribution which it makes to mathematical text-book literature are in no way adequately suggested by the title. It bears little resemblance to the text-book with which we are familiar under this name, but represents pioneer work in the spirit of modern advances in algebra and geometry. The author has chosen the analytic method of attack because, as he says in the preface, it "makes it possible to capitalize the student's collegiate training in algebra, analytic geometry, and calculus, and at the same time to articulate the subject with his future mathematical work."

The emphasis and spirit of the work are even more strongly algebraic than this would suggest. In fact the applications to geometry of one and two dimensions of the invariant theory of binary and ternary forms is the field to which Professor Winger would introduce the student. It would not be easy to find a satisfying short title for these chapters on the geometrical interpretation of modern algebra, and perhaps the author was wise in not trying to disclose in the title the exact nature of his undertaking. In the following outline the reviewer has attempted not merely to give the author's selection of material but also to suggest the emphasis.

The definition of projective coördinates in one and two dimentions and their transformation discussed in Chapter V may be said to be the goal reached in the first quarter of the book. The projective coördinate of a point on a line is defined as a double ratio expressed in terms of abscissas; homogeneous projective coördinates of a point in a plane are defined formally in terms of the Cartesian equations of the sides of the triangle of reference; while for homogeneous projective coördinates of a line the Plücker equations of the vertices are similarly used.

Leading up to this chapter we have a discussion of essential constants; duality in the plane based on a comparison of Cartesian and Plücker coördinates; classification of the conic defined as the locus of the general equation of the second degree in three homogeneous variables with real coefficients, and of the circle with complex coefficients, as exhibiting the use of the line at infinity and the circular points; and the harmonic properties of the quadrangle and quadrilateral.

In Chapter VI we find a scant forty pages devoted to the "beautiful synthetic treatment of the conic, including Pascal's theorem and its consequences," Brianchon's theorem, poles and polars, and polar reciprocation. Even here our conic is introduced as the result of eliminating the parameter between two projective pencils expressed analytically.

Chapters VII, VIII, and IX, the remaining eighty pages of the second quarter, are occupied with binary geometry: collineations and involutions, polar forms derived by means of a differential operator, and algebraic invariants culminating in the complete system of the binary quartic.

Chapter X, sixty pages, the analytic treatment of the conic, the author says in the preface, may follow Chapter V; but let him who thinks to avoid the algebraic details of the intervening chapters beware. Much of this chapter will be wholly unintelligible without them. He will find, in fact, many explicit references to those omitted pages. The chapter is divided into two parts: the first considers the conic as a rational curve, the three coördinates of a point or line being expressed as quadratic functions of a parameter, and is largely devoted to binary forms on the curve; the second handles the conic as the locus of a ternary equation in point and line coördinates, considering especially polar properties.

Chapter XI opens with a classification of non-singular planar collineations which it follows with a discussion of certain collineation groups and absolute coördinates. This furnishes an introduction to the work of Morley on Reflexive Geometry.

Chapter XII treats of cubic and higher involutions and their applications to rational curves and makes contact with the author's investigations on self-projective curves.

The concluding Chapter XIII, an introduction to non-Euclidean geometry, is based largely on the work of Klein.

The reviewer gladly expresses his thanks to Professor Winger for his book as a treatment of the subject-matter it deals with. Preceded or accompanied by a thorough training in synthetic geometry with due emphasis on construction problems, it will perform a valuable service. But if the title of the book and the author's description of it as "an introductory account for senior college and beginning graduate students" imply an invitation to replace our time-honored courses in synthetic geometry, the reviewer must emphatically express his opinion that such a step would be a sad mistake. While acknowledging the important contributions of the analytic method, he is firmly convinced that the synthetic procedure must not be discarded, but must be given a large place in introductory courses if that power of visualization which Reye claimed projective geometry could develop is to be attained.

Of course any adequate appreciation of the historical development of the subject cannot neglect the synthetic. The footnote on page 116, "Pascal's theorem marks the climax of the classical theory of projective geometry," if it means that development along synthetic lines has been of minor importance since the days of Pascal, conveys a wholly mistaken conception of the origin and growth of modern geometry. One cannot do justice to the achievements on which our present knowledge rests without citing von Staudt, whose name nowhere appears in our text, not to mention a host of others who have advanced synthetic geometry. For the cultivation of the geometrical imagination a little work with axial pencils and the regulus is worth far more to students of the grade of advancement

indicated than a consideration of the "curious and startling properties of isotropic lines"; and duality in space, mentioned only in a footnote, should be dwelt upon at length.

The present tendency to avoid geometrical reasoning, shown in the substitution of the elements of the calculus for some of the best parts of plane analytic geometry; the disinclination to think in terms of space, seen in the decline of elementary solid geometry; and the neglect of drawing and descriptive geometry as important parts of the training of the mathematician bode ill for the future of geometry in this country. How are we to produce worthy successors of the great geometers of the past, if elementary solid geometry, synthetic projective geometry, and descriptive geometry are to be thrown on the scrap-heap of discarded disciplines or relegated to a place among the mechanical appliances of the engineer?

The reviewer wishes he could speak only words of praise of the way in which Professor Winger has handled his material, but he would be unfaithful to his task if he failed to mention what he considers a serious defect. At many points he finds a lack of that clearness and accuracy of statement which a teacher would wish to commend to his students. The introductory article of Chapter VI on the projective generation of conics, which, because of its fundamental importance, should receive the greatest care, furnishes a striking illustration. Following the theorem: "The locus of intersections of corresponding lines of two projective pencils is a conic passing through the centers of the pencils," the student is asked to suppose the two pencils as given by the equations

$$(ax) + \lambda(bx) = 0 \qquad \text{and} \qquad (cx) + \lambda(dx) = 0,$$

and is told that these pencils will be projective if he correlates lines having the same parameter; λ is eliminated and the second degree equation,

$$(ax)(dx) - (cx)(bx) = 0, \tag{1}$$

is obtained. This does not by any means prove the theorem, for it is not shown, nor is it true, that he *must* correlate lines having the same parameter to obtain projective pencils. Then without any explanation that the base lines of the pencils may be altered, he is asked to choose the common line as the line $\lambda = 0$.

Later it is asserted that the equation (1) represents a general conic because it contains five essential constants. The chapter on essential constants is scarcely adequate as a basis for showing this, nor is the assertion true, for it is obvious from its origin that equation (1) represents not the general conic but a real conic.

It would seem that only a failure to give the synthetic due consideration could be responsible for the author's definition of a collineation on a line as the result of two perspectivities; such collineations obviously have real double points.

To the same neglect of the synthetic may be attributed the desire to obliterate the invidious distinction between real and imaginary seen in the statements, footnote, page 157, "In a strict projective classification (of collineations) we should not distinguish real and imaginary (double points)," and on page 164, "An elliptic collineation may, however, be transformed into a hyperbolic."

But in spite of this criticism of Professor Winger's writing, it should again be asserted that he has produced a valuable book, one with which every teacher of advanced geometry must be familiar. The numerous exercises, nearly nine hundred in all, and the very full index covering eighteen pages are features which will especially commend its use.

J. W. BRADSHAW.

The Teaching of Mathematics in the Elementary and Secondary School. By J. W. A. YOUNG. New Edition. New York, Longmans, Green and Co., 1924. xviii + 451 pages. Price, $2.20.

It is now about nineteen years since the first edition of this work appeared. These years have brought many changes in the teaching of mathematics, many innovations in text-books, and many new opinions as to the purposes that should characterize the selection of the material that is best suited to the needs of American pupils. Indeed, as one considers the mathematical offering in our schools twenty years ago, and compares it with the offering of today, and as he contrasts present methods of measuring the accomplishments of pupils with those of the early years of the twentieth century, he may be led to feel that the changes have been almost revolutionary. It is with some such ideas in mind that Professor Young has given us the revision of a book that has long been recognized as a standard work for teachers, and that ranks as one of the most sane and scholarly productions of its kind to be found in any language.

The new edition is in large part a reprint of the original one. The first 345 pages are identical, or substantially so, with the first edition; but upwards of a hundred pages have been added, setting forth the changes that the author feels to be the most significant in the last ten years. These changes center about the work of the National Committee on Mathematical Requirements, and in particular the study made by Miss Blair of the question of the disciplinary value of the science, and a consideration of the purposes of the study of mathematics, the modern curriculum, the possibilities of introducing an elementary course in the calculus, the use of the function concept as a basis for curriculum making, and the simplification of the language of mathematics. Professor Young also includes in the added pages a bibliography of various important works on the teaching of mathematics that have appeared since the first edition was printed.

In an article in *Die Rundschau* for September, 1923, George Brandes sets forth in these words Ibsen's method of judging new books: "He judged them by a single quality: the only thing that mattered in his mind was whether they were intimately connected with the soul-life of the author. If so, they were good. If not, they were merely mechanical."

This is the opinion of a great mind, and it is a noble view to take. Professor Young's book is intimately connected with his "soul-life"; it is a good book; it is filled with scholarship of the type that our teachers in America need; it is expressed in a readable and felicitous style; and it fills a need on the part of teachers that no other book so seriously attempts to recognize.

The book will be criticized by the ultraradical school. It has little to say of the modern types of psychological tests, for example, and there are those who see little else in the teaching of anything,—just as a man who insures a house is likely to see nothing in the artistic work of the architect or in the fine details due to the master builder. It assumes that the well-educated man or woman today needs to know what mathematics signifies, just as each needs to know what geography and history and literature and science and the fine arts signify, and it is little concerned with those who talk endlessly about project methods and curricula which shall omit all mathematics and language and science except as these have a direct bearing, as slight as possible, upon some narrow vocation. Against all this educational froth of narrow-minded theorists Professor Young wages silent but effective combat, and his book deserves to be read and reread as one of our best exponents of common-sense mathematics that, freed from many of its early imperfections, should find place in our American schools.

DAVID EUGENE SMITH.

Kreisevolventen und Ganze Algebraische Funktionen. By DR. H. ONNEN. Leipzig, Teubner (Vol. 51, Mathematisch-Physikalische Bibliothek), 1923. 49 pages. Price M. 1.40.

This pamphlet is one of a collection which has received little or no notice hitherto in the pages of the MONTHLY devoted to reviews. Its editors, W. Lietzmann and A. Witting, characterize its volumes as having two purposes:—first to go more deeply into certain elementary problems that have general cultural significance or especial scientific importance; next, without supposing too much prerequisite knowledge on the part of the reader, to introduce him to new fields in pure and applied mathematics. In many cases this prerequisite knowledge does not exceed that furnished by our freshman mathematics, but it might be well to bring to the reading somewhat more than average freshman intelligence. This collection would help solve many a difficulty in the preparation of programs for mathematical clubs, unless, indeed, German has become for the time being a dead language for our undergraduates.

The present volume gives, with considerable detail and with the help of a number of figures, a most interesting geometrical interpretation of the problem of real root separation and approximation for real algebraic equations in one variable. No new algebraic results are obtained,—on this side the author merely obtains from his geometric considerations such well-known elementary theorems as those of Descartes, Budan-Fourier, and Sturm, and illustrates Newton's method of approximation. The interest is in the way he does it.

When a stretched string with a knot on it is unwound from the circumference of a circle, the knot traces a curve called a *first involute* of the circle. If the radius OP_0 of the circle revolves through an angle w, the tracing point P_1 of the unwinding string determines on the tangent at P_0 a segment P_0P_1 of varying length ρ_1, which in all its positions is a radius of curvature of the first involute.

It readily follows that if ρ_0 is the radius of the circle, then

$$\rho_1 = \rho_0 w + \text{constant},$$

the constant depending on the initial value of ρ_1. Similarly we obtain a *second involute* by unwinding a stretched string from the first involute in such a way that its point of tangency is at P_1. From the *second involute* we generate a *third involute* and so proceed to the *nth involute*, whose radius of curvature ρ_n is expressible as a polynomial $f(w)$ of the nth degree in w. The ρ's are so related that each is the derivative with respect to w of its successor.

Conversely, to every polynomial $f(w)$ and its successive derivatives corresponds a chain of involutes. The real roots of $f(w)$ are values of w for which the nth involute has simple or coincident cusps. We can think of the whole chain of involutes corresponding to $f(w)$ as traced by the unwinding process as w increases, and we have thus a picture of the simultaneous variation of the polynomial and its derivatives.

From these fundamental ideas the author proceeds to rediscover, or at least reillustrate, certain familiar chapters of the elementary theory of equations. The style is clear, interesting, graceful.

D. R. CURTISS.

NOTES ON NEW PUBLICATIONS.

Volume one of the *Exterior Ballistic Tables*, planned and initiated by Professor A. A. Bennett, of the University of Texas, while with the Ordnance Department, has just appeared in print as Ordnance Department Publication No. 1107. It is the most extensive table of ballistic functional values ever published. Volume two, computed by refined methods of triple interpolation in the present volume and without new trajectory integration, will present the same data in a form available for range table construction, and while analogous to the Gavre tables will be vastly more comprehensive.

ARTICLES IN CURRENT PERIODICALS.

AMERICAN JOURNAL OF MATHEMATICS, volume 46, no. 3, July, 1924: "Geometrical aspects of the Abelian modular functions of genus four" by A. B. Coble, 143–192; "The curve of ambiance" by F. Morley, 193–200; "On a class of invariant subgroups of the conformal and projective groups in function space" by I. A. Barnett, 201–214.

ANNALS OF MATHEMATICS, second series, volume 25, no. 2, December, 1923: "A contribution to the theory of closed chains" by A. Arwin, 91–117; "On the characterization of the set of points of λ-continuity" by H. Blumberg, 118–122; "On the Ampere-Cauchy derived functions" by H. L. Smith, 123–136; "Note on certain semi-invariants of n-lines" by L. P. Copeland, 137–141; "The Fredholm theory of the Stieltjes integral equations" by C. A. Fischer, 142–158; "Rectilinear congruences referred to special surfaces" by M. C. Foster, 159–180; "Parallel propagation of a vector around an infinitesimal circuit in an affine-connected manifold" by J. L. Synge, 181–184.

BULLETIN OF THE AMERICAN MATHEMATICAL SOCIETY, volume 30, no. 7, July, 1924: "The equation of the eighth degree" by A. B. Coble, 301–313; "Group of a set of simultaneous algebraic equations" by L. Weisner, 314–316; "On a type of plane unicursal curve" by H. Hilton, 317–321; "Surfaces with orthogonal loci of the centers of geodesic curvature of an orthogonal

system" by M. Foster, 322–327; "Quadratic fields in which factorization is always unique" by L. E. Dickson, 324–334; "The Jacobian of a contact transformation" by E. F. Allen, 335–337; "Integro-differential invariants of one-parameter groups of Fredholm transformations" by A. D. Michal, 338–344; "Reductions of enumerations in homogeneous forms" by E. T. Bell; "The scientific work of Joseph Lipka" by W. C. Graustein, 352–356; "Extension of Bernstein's theorem to Sturm-Liouville sums" by E. Carlson, 230–240; "An existence theorem" by E. Hille, 241–248; "On the complete independence of the postulates for betweenness" by W. E. Van de Walle, 249–256; "A new set of postulates for betweenness, with proof of complete independence" by E. V. Huntington, 257–282.

L'ENSEIGNEMENT MATHÉMATIQUE, volume 23, no. 5–6, July, 1923: "Sur l'inversion des produits arithmétiques" by E. T. Bell, 305–308.

PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES, volume 10, no. 7, August, 1924: "Concerning upper semi-continuous collections of continua which do not separate a given continuum" by R. L. Moore, 356–360.

QUARTERLY JOURNAL OF PURE AND APPLIED MATHEMATICS, volume 50, no. 2, August, 1924: "On surfaces whose asymptotic curves are cubics" by C. H. Sisam, 149–153; "Some two-dimensional loci" by J. L. Walsh, 154–164.

TRANSACTIONS OF THE AMERICAN MATHEMATICAL SOCIETY, volume 26, no. 2, April, 1924: "On the expansion of analytic functions in series of polynomials" by J. L. Walsh, 155–170; "Operations with respect to which the elements of a boölian algebra form a group" by B. A. Bernstein, 171–175; "Isometric W-surfaces" by W. C. Graustein, 176–204; "Space-time continua of perfect fluids in the general relativity" by L. P. Eisenhart, 205–220; "Equivalent rational substitutions" by J. F. Ritt, 221–229.

UNDERGRADUATE MATHEMATICS CLUBS.

All reports of club activities should be sent to H. J. ETTLINGER, 2910 Harris Park Ave., Austin, Texas.

CLUB ACTIVITIES.

PI MU EPSILON OF SYRACUSE UNIVERSITY, Syracuse, N. Y.
[*1923*, 40.]

In the academic year 1922–1923 twenty-two members were elected, one instructor, two graduate students and nineteen undergraduates, among them two advanced students in the College of Business Administration. In the year 1923–1924 thirty-six members were elected, classified as follows: faculty three, graduate students two, undergraduates thirty-one; according to colleges, graduate school two, liberal arts twenty-three, applied science nine, business administration two.

The officers for the year 1922–1923 were: director, Otto Gelormini, faculty; vice director, I. S. Carroll, faculty; secretary, Olive Jakway '23; treasurer, Otis P. Hendershot '23; librarian, Helen Franklin '23. The executive committee consisted of the five above-named officers and four additional members: Olga Pfau '23, Georgia Mason '23, Margaret Smith '23, Vivian B. Peckham '23. The scholarship committee was F. F. Decker and I. S. Carroll, faculty members. The officers for 1923–1924 were: director, I. S. Carroll, faculty; vice director, May J. Sperry, faculty; secretary, Eleanor A. Carpenter '24; treasurer, Vivian B. Peckham '24; librarian, Julia W. Bower '25. The executive committee consisted of the five above officers and the following four additional members: Otis P. Hendershot, Gr., Ruth Lyons '24, Adele Armstrong '24, George Howell '24. The scholarship committee was composed of W. G. Bullard, May N. Harwood, faculty, Freda Jones, Helene Aldrich, Vivian B. Peckham '24. The officers elected to serve during the year 1924–1925 are: director, May N. Harwood, faculty; vice director, May J. Sperry, faculty; secretary, Vera Keeney '25; treasurer, Reginald Steel '25; librarian, Dorothy Park '25. The additional members of the executive committee are Helen O'Donnell '26, Warren Lyon, Gr., Louis Rees, Gr., Kenneth Robertson '26.

The following programs were given:

November 27, 1922: Initiation. Dr. Bullard spoke on "History of Pi Mu Epsilon" and Dr. Roe on "The symbols of Pi Mu Epsilon."

December 18, 1922: "The application of mathematics to the derivation of physical formulæ from experimental data" by Otis P. Hendershot '23.

February 19, 1923: "Illustrations of calculus proofs of physical principles" by Georgia Mason '23. "Volume of a tetrahedron in terms of the coördinates of its vertices" by Olga M. Pfau '23.

March 19, 1923: Initiation. Drs. Decker, Bullard and Roe addressed the new members.

April 16, 1923: "Development of notation and calculation" by Helen I. Franklin '23. "Development of Euclidean geometry" by Olive Jakway '23.

During the year 1922–1923 two socials were held, a wiener roast in the fall and a Christmas party. During the year 1923–1924 a picnic and a Christmas party were given to which all majors and minors in the department were invited.

November 12, 1923: Initiation. Drs. Roe and Bullard addressed the new members especially.

December 12, 1923: "Higher plane curves" by Myra I. Johnson, Gr. "Problems of Equilibrium" by Otis P. Hendershot, Gr.

March 15, 1924: Initiation banquet. All alumni and members of other chapters were invited. Sixty-five were present. Director Carroll was toastmaster and on the subject of "Powerful tools of modern mathematics" called for treatment of the following: "Pointers," Vice-chancellor Graham; "Chalk," Professor Lyon; "Red ink," Professor Harwood; "Tables—banquet and log," Professor Bryant; "The calculus of ideals," Dr. Roe.

April 7, 1924: "Some curiosities of ancient mathematics" by Freda Jones '24. "Railroad curves" by Robert Manly '24. "Generalizations and specializations" by Dr. Roe.

April 28, 1924: "Parallel operations of electro-generators" by Henry J. Hall '24. "Applications of mathematics to engineering" by Milliard C. Rowley '24. "Military ciphers" by Professor Lyon.

May 12, 1924: "Archimedes" by Marie Dodge '24. "The development of the calculus" by Mildred Buck '24. "Differential equations" by Vivian B. Peckham '24.

Among the memberships held by members of the Syracuse chapter in other scholarship organizations for the year 1923–1924 are the following numbers: Phi Beta Kappa nineteen, Phi Kappa Phi eighteen, Sigma Xi fifteen, Tau Beta Pi ten.

(Report by Professor E. D. Roe, Jr.)

The Euclidean Circle of the University of Indiana, Bloomington, Ind. [*1923*, 336.]

The following program was given by the Euclidean Circle of the University of Indiana for the year 1923–1924:

October 15, 1923: "Two great figures in the theory of equations" by Miss Eva Graham.

November 5, 1923: "History of great learned societies" by Miss Mary Martin.

November 19, 1923: "The disciplinary value of mathematics" by President W. L. Bryan.

December 10, 1923: "Training of mathematics teachers at Indiana University" by Professor D. A. Rothrock.

January 7, 1924: "Student life in mediæval universities" by Miss Jeanett Grubb. "The curricula of medieval universities" by Mr. Lionel Martin.

February 6, 1924: "Magic squares" by Miss Mary Sangernebo.

March 14, 1924: "History of scales of notation" by Miss Hazel Butler. "Properties of scales of notation" by Miss Dorothy Munns. "Mathematical paradoxes" by Mr. C. E. McClintock.

March 17, 1924: "The ideal mathematics teacher" by Dean Agnes E. Wells.

March 31, 1924: "Relativity" by Mr. B. A. Howlett. "Constructions with ruler and compasses" by Mr. James Woodburn.

April 21, 1924: "History of the theory of numbers" by Miss Dorothy Ridgway. "Some theorems in the theory of numbers" by Mr. Herschel Newsom.

(Report by Professor K. P. Williams.)

The Mathematics Club of Cooper Union, New York City.

[*1924*, 146.]

The following officers served for the year 1923–1924: president, Fred Buhrendorf '25; vice-president, Barnett Emmerich '25; secretary, Hector Audino '25; faculty advisers, Professor H. W. Reddick and W. J. Pickett. The annual prize, a polyphase duplex slide rule, given by the Club to the member of the first year class having the highest average in mathematics, was won by Samuel Lubkin '27.

Meetings were held on alternate Thursdays as follows:

November 1, 1923: An exhibition of mental calculations by Somesh Chandra Bose, Hindu mathematical prodigy.

November 15, 1923: "Sets of integers representing the edges and the diagonal of a rectangular parallelopiped" by Fred Obergfell '25.

December 6, 1923: "The Russian peasant method of multiplication" by Samuel Lubkin '27.

December 20, 1923: "History of the decimal point" by James L. Duncan '27.

January 10, 1924: "Finding the Dominical letter" by Samuel Feldman '27.

January 24, 1924: "The duodecimal system" by Fred Buhrendorf '25.

February 7, 1924: "Theorems about the nine point circle" by Fred Miller '26.

February 21, 1924: "Number systems" by Fred Van der Voort '25.

March 6, 1924: "A mechanical device for trisecting an angle" by Isidor Fankuchen '26.

March 20, 1924: "An instrument for solving certain cubic equations" by H. H. Barcus, instructor.

April 3, 1924: Adoption of the constitution and election of officers for the coming year.

(Report by Hector Audino, secretary.)

The Junior Mathematics Club of the University of Chicago, Chicago, Ill.

[*1923*, 401.]

Officers elected for the year 1923–1924 were: president, L. M. Graves, Gr.; secretary and treasurer (fall and winter), Miss McCracken, Gr.; secretary and treasurer (spring), Miss Johnson, Gr.; chairman of program committee, M. H. Ingraham, Gr.; chairman of social committee, Jewell Hughes, Gr. Two social meetings were held during the year. At the regular meetings the following papers were presented:

October 31, 1923: "Development of mathematical notation" by Marguerite Darkow, Gr.

December 12, 1923: "The library" by Dr. Mayme Logsdon.

January 23, 1924: "Curve fitting" by R. W. Barnard, Gr.

February 6, 1924: "Arithmetic—can you recognize it?" by Echo Pepper, Gr.

February 27, 1924: "Closure" by M. H. Ingraham, Gr.

March 9, 1924: "Transfinite numbers" by L. M. Graves, Gr.

April 9, 1924: "Notes on mathematics" by Professor E. H. Moore.

April 30, 1924: "Continued fractions" by Jewell Hughes, Gr.

May 14, 1924: "Homogeneous coördinates and abridged notation in geometry" by J. A. Nyswander, Gr.

May 25, 1924: "Who has been who in mathematics?" by the undergraduate members of the club.

(Report by E. D. Pepper.)

The Undergraduate Mathematics Club of the University of Iowa, Iowa City, Iowa.

[*1923*, 402.]

The following officers served for the year 1923–1924: president, Eric E. Ericson, M.S. '23; secretary, Howard K. Hughes '23. The club voted at the first meeting that each speaker be asked to write a resumé of his talk in a book provided for the purpose, and it is planned to keep this book as a permanent record of all talks to be given in the future. The meetings during the year were held as follows:

November 22, 1923: "The general number" by Eric E. Ericson, M.S. '23.

March 13, 1924: "On pencils of conics" by Howard K. Hughes '23.

March 24, 1924: "Some properties of involution of points on a line" by John C. Bennett, M.S. '24.

(Report by Howard K. Hughes, secretary.)

The Junior Mathematics Club of the University of Wisconsin, Madison, Wis.

[*1923*, 274.]

The officers for the year 1923–1924 were as follows: president, Myrl A. Summers '24; vice-president, Sarra Abrams '24; secretary-treasurer, Anna Gebhardt '24. The following meetings were held:

October 16, 1923: Picnic.

November 1, 1923: Business.

November 8, 1923: Song. "Sheep and lambs" by Sidney Homer, sung by Gertrude Haase '24. "Shoe and stocking stories" by Professor Arnold Dresden.

November 22, 1923: "Ancient history of mathematics in Egypt and Babylonia" by Mildred Krohn '24.

December 13, 1923: Piano selections by Professor Arnold Dresden. "The American Mathematical Society" by Professor E. B. Van Vleck.

January 10, 1924: "Mathematics in ancient Greece" by Estelle Stone (Fellow).

February 14, 1924: "Some phases of geometry" by Professor W. W. Hart.

February 28, 1924: "Mathematics in China" by Frank Hsi-Lu Chang '24. "Mathematics in Russia" by Sarra Abrams '24.

March 13, 1924: "Mathematics of the Renaissance" by Ethel Schilling, Gr. "Non-Euclidean geometry" by Grace Agnes Kennedy (Scholar). "Mathematical wrinkles" by Edward Hlinak '24.

March 27, 1924: "The lunes of Hippocrates" by Professor L. W. Dowling.

April 24, 1924: Joint meeting of Junior and Senior Mathematical Clubs. Junior Club presented an original one act play entitled "The $(n-1)$th meeting of the infinite Mathematical Society."

May 10, 1924: "American mathematicians" by Irene Salb '24. "Mathematical courses of study in Germany, France and England" by Ellis Heineman '25.

May 22, 1924: Business meeting. The following officers were elected for next year: president, Ruth Miller '25; vice-president, Ellis Heineman '25; secretary-treasurer, Elizabeth Breitzman '25. (Report by Miss Summers.)

Student Scientific Society, Swarthmore College, Swarthmore, Pa.

[*1919*, 168.]

The Mathematical and Astronomical Club formerly existing at Swarthmore College was changed a little over a year ago into what is known as the Student Scientific Society. The membership consists of the students of mathematics, astronomy, physics, chemistry and biology.

Three meetings and a business meeting were held during 1923–1924. At the first, Earl L. Williams and Bevan T. Sharples reported on "The eclipse of the sun on September 10th, 1923." These men were members of the party that accompanied Professor John A. Miller to make observations of the eclipse. At the second meeting of the Club, Professor W. R. Wright of the Physics Department made an address on "Educated motors." At the third meeting, the Club was addressed by Dr. Spencer Trotter of the Biology Department on a report of his summer's observations in the East Indies. (Report by Professor Miller.)

The Mathematics Club of Wellesley College, Wellesley, Mass.

[*1922*, 419.]

The following topics were discussed at meetings of the Wellesley Mathematics Club held during the year 1923–1924:

December 3, 1923: "Work in English libraries" by Professor Helen A. Merrill. Mathematical charades.

January 22, 1924: "Decimal fractions" by Mrs. W. C. Graustein.

March 13, 1924: "Eight queens problem" by Margaret Harris. "Knight problem" by Professor Merrill. "Simultaneous equations" by Jeanette Greener. "Problem concerning the divisibility of cubes" by Shirley Mason.

April 22, 1924. "Linkages" by Professor Morley of Worcester Polytechnic Institute.

THE MATHEMATICAL CLUB OF HAMLINE UNIVERSITY, St. Paul, Minn.
[*1923*, 402.]

For the year 1923–1924 the officers were: president, Lester H. Vetter '25; secretary-treasurer, Ara M. Griffith '24; social chairman, Helen M. Berdan '25. The following meetings were held in 1923–1924:

October 17, 1923. Business meeting and election of officers. "The construction of maps" by Professor R. A. Johnson.

November 21, 1923. "Flatland" by Helen Berdan '25. "Computation of logarithms" by Lester Vetter.

December 12, 1923. "Euler squares" by Ara Griffith. "The method of moments" by Wayne Canfield.

January 16, 1924. "Leibnitz" by Doris Shave. "Development of the number concept" by Victor Westman.

February 20, 1924. "Magic squares" by Hazel Shore. "Various mathematical problems" by Helen Jones.

March 19, 1924. "The measurement of time" by Beth Bishop. "Some practical problems in insurance" by Lester Vetter.

April 24, 1924. Open meeting. "Correlations" by Professor Dunham Jackson of the University of Minnesota.

May 21, 1924. Picnic. "The reform of the calendar" by Wilda Miller. "Astrology" by Grace Woolsey. Officers were elected for 1924–1925 as follows: President, Hazel Shore '25; secretary-treasurer, Grace Woolsey '26; social chairman, Wilda Miller '25.

(Report by Professor Johnson.)

PROBLEMS AND SOLUTIONS.

EDITED BY B. F. FINKEL, OTTO DUNKEL, AND H. L. OLSON.

Send all communications about Problems and Solutions to B. F. FINKEL, Springfield, Mo.

PROBLEMS FOR SOLUTION.

[N.B. Problems containing results believed to be new, or extensions of old results are especially sought. The editorial work would be greatly facilitated if, on sending in problems, proposers would also enclose any solutions or information that will assist the editors in checking the statements. In general, problems in well-known textbooks, or results found in readily accessible sources, will not be proposed as problems for solution in the MONTHLY. In so far as possible, however, the editors will be glad to assist members of the Association with their difficulties in the solution of such problems.]

3101. Proposed by R. E. GAINES, University of Richmond, Va.

A variable conic passes through four fixed points. Show that the locus of its center is a conic. Determine the arrangement of the four points so that this locus shall be a circle and discuss the result. This problem is treated in texts on projective geometry, but a simple analytical treatment is desired.

3102. Proposed by R. E. GAINES, University of Richmond, Va.

For the cardioid, $\rho = 1 + \cos\theta$, (*a*) find the maximum chord, (*b*) find the maximum chord parallel to the axis.

3103. Proposed by OTTO DUNKEL, Washington University.

Given the equation

$$y = \sum_{i=1}^{i=\infty} \frac{(i+1)^{i-1}}{i!} x^i, \qquad |x| < 1/e,$$

find x in terms of y in a finite form.

3104. Proposed by OTTO DUNKEL, Washington University.

If $f(x)$ is a single-valued and continuous function of x in the interval $a \leq x \leq b$ which is not identically zero and which satisfies the inequality $0 \leq f(x) \leq M$, show that

$$0 < \left[\int_a^b f(x)dx\right]^2 - \left[\int_a^b f(x)\cos x dx\right]^2 - \left[\int_a^b f(x)\sin x dx\right]^2 \leq M^2(b-a)^4/12.$$

3105. Proposed by W. A. GRANVILLE, Chicago, Illinois.

Find the length of the arc of the cissoid, $\rho = 2a\tan\theta\sin\theta$, from $\theta = 0$ to $\theta = (\pi/4)$.

3106. Proposed by EDWARD CONDON, University of California.

A spool of thread rolls without slipping on a horizontal plane. It is of radius r_1 and if it rolls from left to right the thread unwinds from the drum part of the spool radius r_2 ($< r_1$). Initially the spool is at rest and the thread, leaving the spool in a direction perpendicular to the axis of the spool, passes over a pulley (considered of zero radius) which is at h above the plane and at horizontal distance l to the left of the point of contact of spool and plane. A weight w is fixed to the thread after it has passed over the pulley.

Determine the motion of the spool, assuming that there is no loss by friction or otherwise of the total energy of the system.

SOLUTIONS.

2949 [1922, 29], [Corrected; 1922, 420]. Proposed by J. B. REYNOLDS, Lehigh University.

Find the lateral area of the cone with vertex at $(0, 0, h)$ and whose base is the epicycloid

$$2x = a(3\cos\theta - \cos 3\theta), \qquad 2y = a(3\sin\theta - \sin 3\theta).$$

SOLUTION BY OTTO DUNKEL, Washington University.

The given epicycloid is the locus of the point P fixed on the circumference of a circle of radius $a/2$, center C, which rolls on a fixed circle with center O and radius a. At the beginning of the rolling the point P is at A on the circumference of the circle O. Consider the position when the point of contact of the two circles is at M, and produce the diameter NCM to O, and let $\angle NOA = \theta$. Then NP is the tangent to the epicycloid. Draw the diameter PCP' and let $P'O$ cut PM produced in E. Then EP is the radius of curvature, and the figure gives $EP = (3/2)MP = (3/2)a\sin\theta$. Thus $ds = 3a\sin\theta d\theta$. The element of area, dA, of the lateral surface of the cone, with the epicycloid as base and vertex, V, vertically above O at the height h, is the triangle with base ds and vertex at V. Draw the perpendicular OK from O to NP produced; then VK, the altitude of the little triangle, is $\sqrt{h^2 + OK^2} = \sqrt{h^2 + 4a^2\sin^2\theta}$. Therefore

$$\begin{aligned} A &= 12a^2\int_0^{\pi/2}\sqrt{n^2 - \cos^2\theta}\sin\theta d\theta, \qquad n^2 = (h^2 + 4a^2)/4a^2, \\ &= 6a^2\left[\sqrt{n^2-1} + n^2\sin^{-1}\left(\frac{1}{n}\right)\right], \\ &= 3ah + \frac{3(h^2+4a^2)}{2}\tan^{-1}\left(\frac{2a}{h}\right). \end{aligned}$$

3043 [1923, 403 and 1924, 358]. Proposed by O. D. KELLOGG, Harvard University.

(*Corrected statement.*) Let T denote an open continuum of the xy-plane, say the interior of a smooth simple closed curve. Then if U is continuous in T, and is such that

$$\iint_T U\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right)dxdy = 0 \tag{1}$$

for all functions V with continuous second derivatives in T, and such that (*a*) the normal derivatives of V vanish on the boundary of T, or, (*b*) the boundary not being a smooth curve, the first derivatives of V at a point P approach 0 as P approaches any boundary point of T, U is harmonic in T, *i.e.*, U satisfies Laplace's equation $(\partial^2 U/\partial x^2) + (\partial^2 U/\partial y^2) = 0$.

NOTE BY THE EDITORS: A solution, by DR. H. E. BRAY, of the problem as now correctly stated has already appeared in the MONTHLY (*1924*, 358). It is believed, however, that the interest and importance attached to this problem warrants the publication of a second solution.

SOLUTION BY THE PROPOSER.

The original statement of this problem contained an oversight. The condition there given was that V should vanish on the boundary of T.

A well-known theorem in potential theory states that the value of a function which is harmonic in a region T is, at any point P, the arithmetic mean of its values on any circle in T with center at P. Koebe has proved a converse of this theorem (*Sitzungsberichte d. Berliner Math. Gesellschaft*, vol. 5 (1906), p. 39), namely, if U is continuous in T, and assumes at each point, P, of T the arithmetic mean of its values on any circle in T with center at P, then U is harmonic.

If the hypothesis of Koebe's theorem were not fulfilled by the function U of the present problem, there would be in T a point, P, and a circle, C, entirely in T, with P as center, such that

$$U(P) \neq \frac{1}{2\pi}\int_0^{2\pi} U(B)d\vartheta, \tag{2}$$

where B is the point on C with vectorial angle θ. We shall show that the relation (2) is incorrect, so that U must satisfy the conditions of Koebe's theorem, and hence be harmonic.

With the use of polar coördinates, with P as pole, the condition (1) on U may be written

$$\iint_T U\left(\frac{\partial}{\partial r} r \frac{\partial V}{\partial r}\right) dr d\vartheta = 0 \tag{3}$$

for all allowable V. Among the allowable V is one which we proceed to form. Let c denote the radius of C, and let α be a positive parameter, restricted to be less than $c/3$, and less than the minimum distance between C and the boundary of T. We then equate $\frac{\partial}{\partial r} r \frac{\partial V}{\partial r}$ to a continuous function $f(r)$, which is positive for $0 \leqq r \leqq \alpha$, negative for $c - \alpha \leqq r \leqq c + \alpha$, and zero elsewhere, and such that $\int_0^{c+\alpha} f(r)dr = 0$. The differential equation thus obtained has a solution, V, which is continuous, together with its partial derivatives of the first two orders, and whose first derivatives vanish outside the circle $r = c + \alpha$. This solution is an allowable V.

We now carry out the integration with respect to ϑ in (3), in which V is to be the function just determined, writing $\overline{U}(r) = \frac{1}{2\pi}\int_0^{2\pi} U(r, \vartheta)d\vartheta$:

$$\int_0^{\alpha} \overline{U}(r)f(r)dr + \int_{c-\alpha}^{c+\alpha} \overline{U}(r)f(r)dr = 0.$$

If the law of the mean be used, this equation leads to

$$\overline{U}(\theta'\alpha) = \overline{U}(c + \theta''\alpha), \qquad (0 < \theta' < 1, \quad -1 < \theta'' < 1).$$

Since U is continuous, and since this last equation holds for all positive α near 0, we conclude that

$$\overline{U}(0) = \overline{U}(c)$$

so that the relation (2) is disproved, as desired.

The problem was also solved by Dr. Wiener. He too used Koebe's theorem, but was able to give to the rest of the treatment a somewhat more elegant, if less elementary form, by use of a theorem to the effect that if a function is orthogonal on a given interval to all continuous functions themselves orthogonal to 1, that function is a constant.

3053 [1924, 49]. Proposed by J. LENSE, Vienna University.

Let

$$a_1 = a, \qquad a_2 = a^{a_1}, \qquad a_3 = a^{a_2}, \quad \cdots \quad a_{n+1} = a^{a_n}, \quad \cdots.$$

Discuss $\lim_{n=\infty} a_n$ as a function of a. (The limit exists also for some values of $a > 1$.)

SOLUTION BY THE PROPOSER.

First, we suppose $0 < a < 1$. Then we have $1 > a_2 > a_1$, $a_1 < a_3 < a_2$, $a_2 > a_4 > a_3$, $a_3 < a_5 < a_4$, $\cdots$, and generally,

$$0 < a_1 < a_3 < a_5 < \cdots < a_{2n-1} < \cdots;$$
$$1 > a_2 > a_4 > a_6 > \cdots > a_{2n} > \cdots;$$

and $a_{2i-1} < a_{2k}$ for $i, k = 1, 2, \cdots$ to inf. Therefore, there are two limits: $\lim_{n=\infty} a_{2n-1} = x$ and $\lim_{n=\infty} a_{2n} = y$ and $x < y$. The limits are solutions of the following equations:

$$a^x = y, \qquad a^y = x.$$

Both curves intersect at one point for all values of a in the interval $\frac{1}{e^e} \leqq a \leqq 1$; in this point $x = y$.

They intersect at three points for all values of a in the interval $0 < a < \frac{1}{e^e}$; these points have the coördinates (x_1, y_1), (x_2, y_2), (x_3, y_3) and we have $x_1 < y_1$, $x_2 = y_2$, $x_3 > y_3$, $x_3 = y_1$, $x_1 = y_3$.

For all values of a in the interval $1 < a < \sqrt[e]{e}$ the curves intersect at two points (x_1, y_1), (x_2, y_2), for which we have $x_1 = y_1$, $x_2 = y_2$, $x_1 < x_2$. The curves do not intersect when $a > \sqrt[e]{e}$. Therefore there is one limit $x = y$ for $\frac{1}{e^e} \leqq a \leqq 1$. Because $\lim_{a=0} a_{2n-1} = 0$ and $\lim_{a=0} a_{2n} = 1$, there are two different limits $x < y$ for $0 \leqq a \leqq \frac{1}{e^e}$ and we have $\lim_{a=0} x = 0$ and $\lim_{a=0} y = 1$.

Now let $1 < a < \sqrt[e]{e}$. Then we have

$$1 < a_2 < \sqrt[e]{e}^{\sqrt[e]{e}}$$

$$1 < a_3 < \sqrt[e]{e}^{\sqrt[e]{e}^{\sqrt[e]{e}}}$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$1 < a < a_2 < a_3 < \cdots < a_n < \cdots.$$

Therefore there exists $\lim_{n=\infty} a_n$, if $\lim_{n=\infty} a_n$ exists for $a = \sqrt[e]{e}$. But we have

$$\sqrt[e]{e} < e, \quad \sqrt[e]{e}^{\sqrt[e]{e}} < e, \quad \sqrt[e]{e}^{\sqrt[e]{e}^{\sqrt[e]{e}}} < e, \quad \cdots \qquad \text{and} \qquad \sqrt[e]{e} < \sqrt[e]{e}^{\sqrt[e]{e}} < \sqrt[e]{e}^{\sqrt[e]{e}^{\sqrt[e]{e}}} < \cdots,$$

therefore, $\lim_{n=\infty} a_n \leqq e$ for $a = \sqrt[e]{e}$. The limits $\lim_{n=\infty} a_n$ and $\lim_{n=\infty} a_n \Big|_{a=\sqrt[e]{e}}$ existing for $1 < a < \sqrt[e]{e}$, are given by the solution $x_1 = y_1$ of the two equations mentioned above in the interval $1 < a < \sqrt[e]{e}$. For $a = \sqrt[e]{e}$ we have $\lim_{n=\infty} a_n = e$. Because the curves do not intersect for all values of $a > \sqrt[e]{e}$, we have no limit in this interval.

Conclusion. $\lim_{n=\infty} a_n$ exists only in the interval $\frac{1}{e^e} \leqq a \leqq \sqrt[e]{e}$. If we denote a by x and $\lim_{n=\infty} a_n$ by y, we shall get it as solution of the equation $y = x^y$. Therefore, we have to discuss this curve in the interval $\frac{1}{e^e} \leqq x \leqq \sqrt[e]{e}$. It is easily shown that y is a continuous function of x always increasing from $x = e^{1/e}$ till $x = \sqrt[e]{e}$. All its derivatives exist and are continuous functions of x, the point $x = \sqrt[e]{e}$ being excepted. The curve has a point of inflexion for $x = 0.396$, $y = 0.582$. In the first part of the interval, it is concave; in the second convex quâ the x-axis. In the following table are the coördinates of some points of the curve:

$x = \frac{1}{e^e} = 0.0763$	0.396	1	$\sqrt[e]{e} = 1.44$
$y = \frac{1}{e} = 0.368$	0.582	1	$e = 2.72.$

3054 [1924, 49]. Proposed by S. A. COREY, Des Moines, Iowa.

Construct three triangles with vector sides a, b, c; d, e, f; g, h, k, such that $d = a$, $g = 2a$, $e = 2b$, $h = b$. Prove that $a^2 + b^2 + 4c^2 = f^2 + k^2$.

Solution by J. A. Bullard, U. S. N. A.

Construct the triangles as shown in the figure and also draw the vector $2c$ as shown. Then

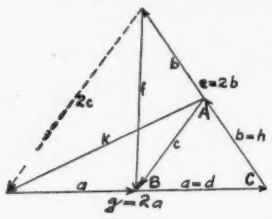

Fig. 1.

$$b^2 + (2c)^2 - 4bc\cos A = k^2,$$
$$a^2 + (2c)^2 - 4ac\cos B = f^2,$$

adding

$$a^2 + b^2 + 8c^2 - 4c(b\cos A + a\cos B) = f^2 + k^2;$$

but $b\cos A + a\cos B = c$, and thus $a^2 + b^2 + 4c^2 = f^2 + k^2$.

Also solved by R. P. Agnew, H. C. Bradley, L. Bagley, A. G. Clark, Philip Fitch, J. Q. McNatt, A. Pelletier, H. A. Simmons, and A. S. Wiener.

3059 [1924, 101]. Proposed by Daniel Kreth, Wellman, Iowa.

Given the perimeter and the radii of the inscribed and circumscribed circles, to construct the triangle and calculate the lengths of its sides.

Solution by Louis Weisner, University of Rochester.

The proposed construction is generally impossible as the following analysis shows:

Denoting the sides of the triangle by a, b, c, the perimeter by $2s$, and the radii of the inscribed and circumscribed circles by r and R, respectively, we have

$$r = \sqrt{\frac{(s-a)(s-b)(s-c)}{s}}, \qquad 4R = \frac{abc}{\sqrt{s(s-a)(s-b)(s-c)}};$$

whence $abc = 4rsR$. From the first equation,

$$r^2 s = s^3 - (a+b+c)s^2 + (ab+ac+bc)s - abc.$$

Substituting, $a+b+c = 2s$, $abc = 4rsR$, we obtain $ab + ac + bc = r^2 + s^2 + 4rR$. It follows that a, b, c are the roots of the cubic

$$x^3 - 2sx^2 + (r^2 + s^2 + 4rR)x - 4rsR = 0.$$

It is easy to see that this cubic is a general cubic equation, whose roots cannot be expressed in terms of square roots alone. For example, take $s = 6$, $r = \frac{1}{2}\sqrt{2}$, $R = \frac{17}{8}\sqrt{2}$. Then a, b, c are the roots of $x^3 - 12x^2 + 45x - 51 = 0$, which has three real, irrational, positive roots. Hence a, b, c cannot be expressed in terms of square roots alone and the construction of the triangle is impossible with ruler and compasses.

Remarks on the Above Solution by Otto Dunkel.

The equation for x above apparently does not alone determine the triangle in all cases. If we take $R = 2r$, then geometry shows that for a real triangle the sides must be equal. Now the equation will not have three equal roots unless we impose the further condition $r = s/3\sqrt{3}$. It would be interesting to study the nature of the roots with the single condition $R = 2r$.

Another way of determining the equation for the sides is to eliminate A from the equations $\sin A = a/2R$, $\tan(A/2) = r/(s-a)$. This would give at once the equation above, or with a slight change before reduction

$$y^3 - sy^2 + (r^2 + 4rR)y - sr^2 = 0,$$

where the roots are $s-a$, $s-b$, $s-c$. Expressing the coefficients of these two equations in terms of the roots we would have simple proofs of the two formulæ used above, and also a proof of the formula for the tangent of the half angle in any triangle.

Also solved by William Hoover, W. B. Pierce, and C. K. Robbins.

NOTES AND NEWS.

Readers are invited to contribute to the general interest of this department by sending items to R. W. BURGESS, c/o Western Electric Co., 195 Broadway, New York City.

At the College of William and Mary, Professor J. E. ROWE has been made director of extension, and Miss ELIZABETH MERCER has been appointed instructor of mathematics.

Professor L. L. SILVERMAN, of Dartmouth College, who has just returned from a year's leave of absence in Germany and Russia, has been promoted to a full professorship.

Mrs. ETHELWYN R. BECKWITH has been appointed professor of mathematics at the College for Women, Western Reserve University, for 1924–1925, to serve during the sabbatical leave of Professor ANNA M. PALMIE.

Assistant Professor LACHLAN GILCHRIST, of the University of Toronto, has been promoted to an associate professorship of physics.

Assistant Professor C. C. MAC DUFFEE of Princeton University has been appointed assistant professor of mathematics at Ohio State University.

Dr. J. S. TAYLOR, of the Massachusetts Institute of Technology, has been appointed assistant professor of mathematics at the University of Pittsburgh.

Mr. J. C. TINNER has been appointed professor of mathematics at Wilberforce University.

Mr. H. K. FULMER, of the Georgia School of Technology, has been promoted to an assistant professorship of mathematics.

Assistant Professor A. R. CRATHORNE, of the University of Illinois, has been promoted to an associate professorship of mathematics.

Associate Professor F. R. MOULTON, of the University of Chicago, has been promoted to full professorship.

At St. Olaf College, Northfield, Minnesota, Professor MARTIN NORDGAARD, formerly head of the department of mathematics at Antioch College, has been appointed professor and head of the department of mathematics, and Mr. ARTHUR SOLUM of the University of Minnesota, has been appointed assistant professor.

Mr. E. L. BROWN, for the past 24 years principal of the North High School, Denver, and a charter member of the Association, has been promoted to the position of assistant superintendent of schools, in charge of high schools.

Associate Professor A. S. MERRILL, of the University of Montana, has been promoted to a full professorship of mathematics.

Dr. H. E BRAY, of Rice Institute, has been promoted to an assistant professorship of mathematics.

Dr. J. H. JEANS, of Cambridge University, has been appointed research associate at Mount Wilson Observatory.

The following appointments to instructorships are announced:

Amherst College, Mr. C. S. PORTER.

Bryn Mawr College, Miss ANNA M. LEHR.

Colorado School of Mines, Mr. E. P. MARTINSON.
Cornell University, Mr. H. A. HOOVER.
Georgia School of Technology, Messrs. G. S. BRUTON, G. W. NICHOLSON, L. K. PATTON, H. H. PIXSLEY, D. P. RICHARDSON.
University of Michigan, E. H. WAGNER, L. M. BLUMENTHAL, H. F. SCHIEFER.
University of Oklahoma, Mr. A. E. ANDERSON.

Professor C. B. AUSTIN, of Ohio Wesleyan University, died September 9, 1924, at the age of 73. Professor Austin had for some years been vice-president of the University as well as professor of mathematics.

Associate Professor H. S. EVERETT, of Bucknell University, Lewisburg, Penn., has been promoted to a full professorship.

On November 22, 1924, forty-one mathematics teachers of Southern California gathered in the dining room of the Los Angeles City Club, upon the invitation of Professor E. R. Hedrick. After partaking of a bountiful lunch, the meeting was organized by electing Professor Hedrick Temporary Chairman, and Professor Russell, of Pomona College, Temporary Secretary. Following an informal discussion, it was voted unanimously that it would be desirable to form a Southern California section of The American Mathematical Association and the proper committees were appointed to carry out this plan.

Of the forty-one present, seventeen are members of the Association and most of the others expressed a desire to become members.

CORRECTION: The price of *Charts and Graphs* by K. G. Karsten should be $6.00 and not $4.00 as announced (*1924*, 449).

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RICHMOND. E. D. Grant, H. N. Wright.
TERRE HAUTE. Kennedy, Sousley.
WEST LAFAYETTE. J. C. Bennett, E. M. Berry, Doan, Edington, Graves, Hadley, Hazard, Hodge, Knox, Robbins, R. B. Stone, Zehring.

IOWA. (56)

AMES. Agnew, Brandner, Colpitts, Daniells, Ernsberger, Fleming, Gouwens, J. V. McKelvey, M. M. McKelvey, Pattengill, Roberts, Rogers, Sage, E. R. Smith, Snedecor, Tappan, J. S. Turner.
CEDAR FALLS. Condit, Daugherty, Wester.
CEDAR RAPIDS. L. M. Coffin, Yothers.
DAVENPORT. Yancey.
DES MOINES. Blom, Corey, Moon, Neff, Wifvat.
DUBUQUE. Theobald, Zimmerman.
FAYETTE. Deming.
GRINNELL. McClenon, Rusk.
HOPKINTON. Earhart.
HUBBARD. Reese.
INDIANOLA. C. W. Emmons.
IOWA CITY. Baker, Chittenden, Gwinn, H. K. Hughes, Reilly, Rietz, R. Woods.
LAMONI. Mortimore.
LE MARS. Kime.
MASON CITY. George.
MT. PLEASANT. King.
MOUNT VERNON. McGaw, Moots.
MUSCATINE. Stein.
OSKALOOSA. S. M. Hadley.
SAC CITY. Dickey.
SIOUX CITY. Graber, Van Horne.
UNIVERSITY PARK. Overstreet.
WELLMAN. Kreth.

KANSAS. (44)

BALDWIN CITY. Garrett.
EMPORIA. Rumney.
HAYS. Colyer.
HIGHLAND. T. B. Henry.
IOLA. R. H. Carpenter, F. L. Marshall.
KANSAS CITY. Dougherty, Helwig.
LAWRENCE. Ashton, Babcock, Black, H. E. Jordan, Lefschetz, Marm, U. G. Mitchell, Reagan, G. W. Smith, Stouffer, H. M. Walker, J. J. Wheeler.
MANHATTAN. W. H. Andrews, Hyde, Janes, C. F. Lewis, Lyons, Mossman, Remick, Stratton, A. E. White.
NEWTON. Richert.
OTTAWA. J. L. Bennett, Loewen.
PARSONS. Farner.
PITTSBURGH. W. H. Hill, Hunter, Shirk.
ST. MARY'S. Case.
STERLING. T. Bell.
TOPEKA. Harshbarger, McLatchey.
WELLINGTON. Lynch.
WICHITA. Hoare, W. O. Mendenhall.
WINFIELD. H. S. Myers.

KENTUCKY. (15)

BEREA. Guilliams, Peck.
DANVILLE. Crooks, Fehn.
GEORGETOWN. B. Hall, C. H. Richardson.
LEXINGTON. Andrew, Boyd, J. M. Davis, Downing, Le Stourgeon, E. L. Rees.
PAINTSVILLE. Backer.
STANFORD. E. V. Watts.
WILLIAMSBURG. Vallandingham.

LOUISIANA. (33)

ALEXANDRIA. Touchstone.
BATON ROUGE. J. P. Cole, Daspit, Droz, Guilbeau, Nichols, O'Quinn, S. T. Sanders, Shoptaugh, Webber, Welch.
CLINTON. Petty.
ELTON. B. A. Tucker.

HOMER. Z. Allen.
LAFAYETTE. Stokes.
NAPOLEONVILLE. Lastrapes.
NATCHITOCHES. Frary, Maddox, Sparks.
NEW ORLEANS. H. E. Buchanan, Cope, Daly, Dinwiddie, A. M. Howe, Latimer, Many, J. H. Meyer, Spencer.
PINEVILLE. C. D. Smith.
RUSTON. Pugh.
SHREVEPORT. Hardin.
VIVIAN. J. H. Manning.
ZACHARY. Peters.

MAINE. (10)

BRUNSWICK. Hammond, Moody.
LEWISTON. Ramsdell.
ORONO. Bryan, Hadlock, J. N. Hart.
WATERVILLE. Ashcraft, B. E. Carter, Trefethen.
WOODLAND. A. S. Adams.

MARYLAND. (44)

ANNAPOLIS. Bingley, Bramble, J. A. Bullard, Capron, Clements, Dillingham, Eppes, Garrison, Gaver, Mayer, Rawlins, Robert, Root, J. B. Scarborough, Shenton, J. Tyler.
BALTIMORE. Bacon, Cohen, Harry, Hulburt, F. P. Lewis, L. T. Moore, F. Morley, Murnaghan, Musselman, C. A. Nelson, L. J. Reed, A. C. Robinson, Stanwick, Thomsen.
BRUNSWICK. C. W. R. Crum.
CHESTERTOWN. J. S. W. Jones.
COLLEGE PARK. Gwinner.
EMMITSBURG. Burke.
FREDERICK. L. O. Brown, Packer.
GLENCOE. A. A. Grant.
NEW WINDSOR. Yoder.
RIVERDALE. Le Lacheur, Somers.
ROLAND PARK. Morrow.
WESTMINSTER. B. I. Hart.
WOODSTOCK. E. C. Phillips, J. P. Smith.

MASSACHUSETTS. (90)

AMHERST. Esty, F. C. Moore, W. J. Newlin, Olds, C. S. Porter, W. R. Porter.
BELMONT. Douglass, Downey, Rutledge.
BOSTON. C. A. Benander, Brigham, Bruce, G. W. Evans, Gould, Laurentine, Mode, Osborne, M. M. Smith, Spear, Edwin B. Wilson.
BROOKLINE. A. L. Miller.
CAMBRIDGE. F. H. Bailey, Beatley, Birkhoff, Bradley, Burrows, Coolidge, W. L. Crum, Franklin, Graustein, E. V. Huntington, M. F. Jordan, Kellogg, Kennelly, C. L. E. Moore, Osgood, Passano, F. W. Perkins, H. B. Phillips, L. H. Rice, H. W. Tyler, Walsh, D. E. Whitford, F. S. Woods, Zeldin.
EVERETT. Bryant.
HOLYOKE. Moriarty.
HYDE PARK. Norwood.
LAWRENCE. Lord.
LEXINGTON. Ward.
LYNN. Maizlish.
NORTHAMPTON. S. R. Benedict, Munroe, Rambo, R. G. Wood.
NORTON. G. A. Shook.
PITTSFIELD. Washburne.
SOUTH HADLEY. Doak, Hazlett, E. N. Martin, S. E. Smith.
SPRINGFIELD. Hickox, Marsh.
TUFTS COLLEGE. Bush, Mergendahl, Ransom, Wilkins.
WATERTOWN. Haigler.
WELLESLEY. Anderton, Copeland, Merrill, C. E. Smith, Vivian, Willis, M. M. Young.
WILLIAMSTOWN. Agard, Hardy, V. H. Wells.
WOLLASTON. Gardner.
WORCESTER. E. C. Brown, Gay, Hollis, Kimball, Lazott, Melville, R. K. Morley, Phinney, H. Rice, A. H. Wheeler, F. B. Williams.

MICHIGAN. (66)

ALBION. H. Barton, F. E. Field, Sleight.
ALMA. Clack.
ANN ARBOR. Anning, Blessing, Blumenthal, Bradshaw, Coe, Denton, Dostal, P. Field, S. E. Field, W. B. Ford, J. W. Glover, A. G. Hall, T. H. Hildebrandt, Hopkins, M. F. Johnson, Karpinski, Kazarinoff, Love, Markley, A. L. Nelson, O. J. Peterson, Poor, C. Reid, Rood, Rouse, Running, Schorling, Shohat, Ziwet.
BAY CITY. Shellenberger.
DETROIT. Baldwin, Barlow, Darnell, Mullen, Worden.
EAST LANSING. Crowe, L. C. Emmons, V. G. Grove, R. N. Haskell, H. L. Olson, Plant, Speeker.
FENTON. Tryon.
HIGHLAND PARK. Thome.
HILLSDALE. Herron.
HOLLAND. Lampen.
KALAMAZOO. H. Blair, J. P. Everett, T. O. Walton.
MARQUETTE. Spooner.
MONROE. Paula.
MOUNT PLEASANT. Pearce.
NILES. W. H. Wilson.
OLIVET. Whelan.
ROYAL OAK. Schoonover.
STURGIS. Steirnagle.
YPSILANTI. Barnhill, Gee, Lindquist, Lyman, Matteson, Norton.

MINNESOTA. (42)

COLLEGEVILLE. Winklemann.

DULUTH. Brigetta.
HERON LAKE. L. E. Lunn.
MANKATO. Chapman, A. V. Robbins.
MINNEAPOLIS. Beal, Brink, Brooke, Bussey, Dalaker, Gibbens, W. L. Hart, Hartig, Herrick, D. Jackson, Kirchner, W. H. McEwen, McGuire, C. A. V. Peterson, Priester, Shuman, Shumway, H. L. Smith, Sublette, Thorp, Underhill, Warne, Wilcox.
MOOREHEAD. K. Leonard.
NORTHFIELD. Clement, Gingrich, Nordgaard, M. B. White.
ST. PAUL. R. A. Johnson, Kingery, Mickelson, Reuterdahl, Rupp, F. J. Taylor.
VIRGINIA. C. L. Hancock.
WINONA. Bogard, French.

MISSISSIPPI. (13)

A. AND M. COLLEGE. H. Fox, B. M. Walker.
BLUE MOUNTAIN. Hutchins.
CLINTON. Hitt.
GRENADA. Duncan.
GULFPORT. Mauldin.
HATTIESBURG. Sharp.
JACKSON. Babbitt, B. E. Mitchell.
JONESTOWN. Barr.
UNIVERSITY. Hume, R. Torrey.
WASHINGTON. Gwaltney.

MISSOURI. (43)

CAPE GIRARDEAU. B. F. Johnson, E. H. Thomas.
COLUMBIA. E. F. Allen, Callaway, Haynes, Ingold, Jaeger, P. H. Pepper, Wahlin, W. D. A. Westfall.
FULTON. Sweazey, M. A. Wood.
KANSAS CITY. Cutting, Epperson, Luby, Pierson.
KIRKSVILLE. Cosby, Jamison.
LIBERTY. Fleet.
PARKVILLE. R. A. Wells.
SPRINGFIELD. Finkel, W. N. Thompson.
ST. CHARLES. Karr.
ST. LOUIS. Ammerman, Brennan, A. Davis, Dunkel, Gerst, A. H. Huntington, Nauer, Osborn, Rider, P. Robertson, Roever, Ryan, Shannon, E. Stephens, Weeks, J. M. Young.
TARKIO. Jenison.
WARRENSBURG. J. H. Scarborough.
WARRENTON Knorr.
WEBSTER GROVES. M. B. Clarke.

MONTANA. (6)

BOZEMAN. Weida.
GLASGOW. Calderwood.
HELENA. O'Neill.
MISSOULA. Carey, Lennes, A. S. Merrill.

NEBRASKA. (22)

BETHANY. Osterhout, Sherer.
CERESCO. L. C. Walker.
CRETE. J. N. Bennett.
GIBBON. N. M. Johnston.
GRAND ISLAND. H. Anderson.
HASTINGS. McDill.
KEARNEY. Hanthorn.
LINCOLN. Brenke, Candy, Congdon, Gaba, M. F. Jackson, Kirker, Opp, T. A. Pierce.
OMAHA. H. A. Campbell, T. I. Porter, Wilmer.
PERU. A. L. Hill.
UNIVERSITY PLACE. Howie.
YORK. Feemster.

NEVADA. (2)

RENO. C. Haseman, Shirley.

NEW HAMPSHIRE. (15)

DOVER. Huntley.
DURHAM. G. N. Bauer, Slobin, Wilbur.
EXETER. Sweet.
HANOVER. Beetle, Bill, B. H. Brown, Cook, C. H. Forsyth, Mathewson, Morgan, Silverman, C. E. Wilder, J. W. Young.

NEW JERSEY. (32)

CLINTON. G. H. Hill.
CONVENT STATION. Maskell.
EAST ORANGE. Koch, Mallory, F. H. Robinson.
LAWRENCEVILLE. Durell.
LEONIA. Gafafer, M. S. Taylor.
MORRIS PLAINS. A. E. Johnson.
NEWARK. Conkling.
NEW BRUNSWICK. Carlson, Garretson, R. Morris, R. Thompson, A. A. Titsworth.
PATERSON. Caster.
PRINCETON. E. P. Adams, Alexander, Eisenhart, Fine, W. Gillespie, Hille, H. D. Thompson, Veblen, Wedderburn, Willson.
RIDGEWOOD. Phelps.
RIVERTON. R. R. Wood.
RUTHERFORD. McMackin.
SUMMIT. H. E. Webb.
TRENTON. Colliton.
WOODBURY. DoBell.

NEW MEXICO. (3)

ALBUQUERQUE. Barnhart.
EAST LAS VEGAS. Rodgers.
SOCORRO. Reece.

NEW YORK. (168)

ALBANY. Birchenough, G. M. Conwell.
ALFRED. Seidlin, W. A. Titsworth.
ANNANDALE-ON-HUDSON. Packard.

AURORA. Hollcroft.
BALDWIN. C. C. Grove.
BEECHHURST. E. Berger.
BROOKLYN. Angelica, Bergstresser, W. J. Berry, Bowden, Emery, Kreines, Lehmann, Locke, Rosanoff, Schuyler, Tanzola, G. F. Wilder.
BUFFALO. Harrington, T. H. Milne, Pound, Sherk.
CANTON. Earl.
CLINTON. H. S. Brown, Carruth, Ferry, A. L. Fitch.
DE KALB JUNCTION. H. M. Phillips.
DUNKIRK. Lufkin.
EAST ELMHURST. Hanson.
ELMHURST. Harper.
ELMIRA. Suffa, F. W. Wright.
FLUSHING. P. H. Graham, Oglesby.
GENEVA. W. H. Durfee, W. P. Durfee, Hubbs.
HAMILTON. A. W. Smith.
HEMPSTEAD. Coffin.
ITHACA. Boothroyd, Carver, Farnum, D. C. Gillespie, Hurwitz, MacCreadie, H. B. Meek, H. M. Morse, F. W. Owens, H. B. Owens, Poritsky, Ranum, Shaub, V. Snyder, Tanner, Waltz.
MOUNT VERNON. Breckenridge.
NEW YORK. J. Allen, Auerbach, Autenrieth, Ballantine, Berkeley, V. Blair, W. M. Bond, Brahdy, Brewster, Burdick, R. W. Burgess, G. A. Campbell, Chellborg, R. F. Clark, Dantzcher, C. H. Douglas, Eckersley, Edmonson, Fiske, Fite, Fort, Foster, Frankel, Fry, Hawkes, R. Henderson, Himwich, Hirsch, Hodgdon, Jablonower, Joffe, M. I. Johnson, Kasner, Kunte, Langellotti, Langman, Linehan, J. J. McCarthy, Meder, Merriman, Mirick, H. B. Mitchell, Molina, Mullins, Paaswell, Pedersen, Penn, Pooler, Post, Pride, R. G. Putnam, Reddick, Reeve, Ritt, Saurel, Schmall, Schub, Siceloff, Simons, D. E. Smith, R. F. Smith, R. R. Smith, Spies, W. A. Stevens, H. Thompson, Thorne, Tilly, A. B. Turner, Upton, Waldo, E. Walker, Webster, Wechsler, E. E. Whitford, W. O. Wiley, Woodyard.
OLEAN. Lowry.
PARISH. Church.
PLEASANTVILLE. B. G. Westfall.
POUGHKEEPSIE. Cowley, Cummings, M. E. Wells.
ROCHESTER. Betz, Gale, E. L. Hall, H. Harding, T. R. Long, Silberstein, Watkeys, Weisner.
SCARSDALE. MacNeish.
SCHENECTADY. Hussey, D. S. Morse, Newkirk, A. D. Snyder, Vedder.
SYRACUSE. W. G. Bullard, Carroll, Decker, Lindsey, Secy. Pi Mu Epsilon Frat., Roe, M. Sperry, W. E. Taylor.
TROY. Crockett.
WEST POINT. C. P. Echols.
YONKERS. Hubert, F. W. John, Yanosik.

NORTH CAROLINA. (22)

CHAPEL HILL. Browne, Cain, A. Henderson, M. A. Hill, Hobbs, Lasley.
DAVIDSON. J. L. Douglas.
DURHAM. M. R. Richardson, Robison.
ELON COLLEGE. Amick.
GREENSBORO. G. W. Mendenhall, F. S. Mitchell, Pegram, Strong.
GREENVILLE. M. D. Graham.
GUILFORD COLLEGE. R. L. Newlin, Pancoast.
JAMESTOWN. Ragsdale.
MURFREESBORO. Caldwell.
RALEIGH. Prosser.
WILMINGTON. H. B. Smith.
WINSTON-SALEM. F. H. Jackson.

NORTH DAKOTA. (9)

FARGO. Atwood, Duerner, Householder, I. W. Smith.
JAMESTOWN. T. W. Jackson.
MINOT. De La.
UNIVERSITY. Bibb, Hitchcock.
VALLEY CITY. J. B. Meyer.

OHIO. (95)

ADA. Fairchild, Whitted.
ALLIANCE. Trott.
ATHENS. Borger, F. W. Reed.
BEREA. Dustheimer.
BOWLING GREEN. Overman.
BLUFFTON. Hirschler.
CEDARVILLE. Diederich.
CHAUNCEY. Minister.
CHILLICOTHE. Cornetet.
CINCINNATI. I. A. Barnett, Brand, H .Hancock, Kindle, Lubin, C. N. Moore, E. S. Smith, Wilczewski, Yowell.
CLEVELAND. E. R. Beckwith, V. I. Benander, Focke, W. W. Johnson, B. W. Jones, Justin, McBane, J. E. Merrill, M. Morris, Nassau, Palmié, Simon, C. F. Thomas.
COLUMBUS. C. L. Arnold, Bareis, Bohannan, V. B. Caris, Cottingham, Harmount, Kuhn, MacDuffee, McCoy, Manson, C. C. Morris, Preston, Rasor, Rickard, Singer, R. L. Wilder, Wildermuth.
DAYTON. Hofmann.
DEFIANCE. A. G. Caris.
DELAWARE. G. N. Armstrong, Crane.
GAMBIER. R. B. Allen, Denston.
GRANVILLE. Lemon, F. B. Wiley.
HARRIETTSVILLE. G. S. Jones.
HILLIARD. J. H. Weaver.
HIRAM. E. H. Clarke.

KENT. Manchester.
MARIETTA. Coar, Rea.
NEWARK. Bumer.
NEW CONCORD. C. E. White.
OBERLIN. Cairns, Carr, Sinclair, Yeaton.
OXFORD. W. E. Anderson, Baudin, M. B. Carter, Lange, Schoonmaker, Sheets, Spenceley, Winters.
PAINESVILLE. Freas, A. D. Lewis.
ROSS. Haldeman.
SPRINGFIELD. Tripp.
STEUBENVILLE. Horn.
TIFFIN. J. Pierce.
TOLEDO. Brandeberry, Dancer, Mercedes.
WESTERVILLE. B. C. Glover.
WILBERFORCE. B. Sanders, Tinner, Waits.
WILMINGTON. Spinks.
WOOSTER. Williamson, Yanney.
YELLOW SPRINGS. W. A. Hamilton.

OKLAHOMA. (29)

CHICKASHA. Hawkins.
COALGATE. Ralls.
DALE. R. L. Hicks.
DUNCAN. McBee.
DURANT. A. Berger, Work.
EDMOND. Stewart.
HENRYETTA. Begley.
MIAMI. J. B. Steed, C. S. Whitney.
NORMAN. Court, Barbour, Hassler, D. McFarland, McGilvray, S. W. Reaves, Rohrbaugh, F. L. Smith, J. D. Whitney.
OKLAHOMA CITY. U. Butler, Cornell, Demaud, Meador, L. V. Robinson, Townes.
SHAWNEE. W. T. Short.
STILLWATER. Gundersen.
WEATHERFORD. McCormick.
WILSON. R. O. Webb.

OREGON. (11)

ALBANY. L. W. Moore.
ASTORIA. H. M. Manning.
CORVALLIS. Beaty, C. L. Johnson.
EUGENE. De Cou, McAlister, W. E. Milne, Smail.
PORTLAND. Griffin, Merriss, J. M. Short.

PENNSYLVANIA. (91)

ALLENTOWN. Bauman.
ANNVILLE. Redditt.
BEAVER FALLS. Cleland.
BETHLEHEM. Lyle, Rau, J. B. Reynolds.
BRYN MAWR. Pell, C. A. Scott, S. M. Wolfe.
CAMP HILL. Foberg.
CARLISLE. Landis.
COLLEGEVILLE. Clawson.
CYNWYD. Sensenig.
DEVON. J. A. Clarke.
EASTON. Benner, Doushkess, W. S. Hall, Hatch, W. M. Smith.
GETTYSBURG. Arms.
GROVE CITY. Ramsey.
HARRISBURG. Whited.
HAVERFORD. L. W. Reid, A. H. Wilson.
HUNTINGTON. C. S. Shively.
IRWIN. A. A. Jones.
LANCASTER. R. L. Charles, W. F. Long.
LANSDOWNE. Chambers, Glenn, Gummere.
LATROBE. Seubert.
LEWISBURG. Bartol, H. S. Everett, Gold, Lindemann.
LINCOLN UNIVERSITY. W. L. Wright.
LOCK HAVEN. High.
MEADVILLE. Akers, Wagner.
MECHANICSBURG. N. B. Freeman.
MILLERSVILLE. Seiverling.
MYERSTOWN. Kiess.
NEW WILMINGTON. McCain.
PHILADELPHIA. P. A. Caris, Crawley, J. E. Davis, Eshleman, H. B. Evans, Gehman, F. John, Kline, Levita, Linton, Partridge, Rittenhouse, Rosengarten, Safford.
PITTSBURGH. Baird, Barrett, Bishop, Burley, Geckeler, R. P. Johnson, J. H. Mathews, Riggs, Rosenbach, Simester, Swartzel, Taber, J. S. Taylor, Trytten, Whitman.
SOUTH BETHLEHEM. P. A. Lambert, MacNutt.
STATE COLLEGE. Bushyager, Gravatt, L. S. Johnston, E. D. McCarthy, Shibli, J. M. West, F. G. Williams.
SWARTHMORE. Marriott, J. A. Miller.
SWISSVALE. Foraker.
WASHINGTON. Atchison, Bert, Cardin, R. W. Thomas.
WEST PHILADELPHIA. Latshaw.
WEST PITTSTON. Templin.

PHILIPPINE ISLANDS. (2)

MANILA. Gokhale, Tienzo.

PORTO RICO. (1)

MAYAGUEZ. C. E. Horne.

RHODE ISLAND. (13)

PROVIDENCE. C. R. Adams, Archibald, Batchelder, Burwell, Chace, Currier, Gilman, Hickson, H. P. Manning, R. G. D. Richardson, Sauté, Suesman, Watt.

SOUTH CAROLINA. (14)

CHARLESTON. O. J. Bond, R. H. Coleman.
CLINTON. A. V. Martin.
COLUMBIA. Coker, J. B. Coleman, J. B. Jackson, W. L. Williams.
DOVESVILLE. P. K. Smith.

GREENVILLE. Earle, R. B. Wood.
GREENWOOD. Weber.
HARTSVILLE. C. M. Reaves.
ROCK HILL. Pope.
SALUDA. Ramage.

SOUTH DAKOTA. (10)

ABERDEEN. Mills.
BROOKINGS. I. L. Miller.
CANTON. E. J. Olson.
HURON. Titt.
RAPID CITY. Bowles, McLaury.
SIOUX FALLS. Hacker.
VERMILION. McKinney, Swanson.
YANKTON. Faught.

TENNESSEE. (15)

CHATTANOOGA. Hooper.
FAYETTEVILLE. Boyce.
JACKSON. Hess.
KNOXVILLE. J. D. Bond, Brezler, Ghormley.
MARYVILLE. Knapp.
NASHVILLE. R. V. Blair, S. I. Jones, Roman.
PULASKI. Feagan, Mize.
RIPLEY. Edward B. Wilson.
SEWANEE. S. M. Barton, Claytor.

TEXAS. (71)

ABILENE. Burnam.
AUSTIN. W. L. Ayres, H. Y. Benedict, A. A. Bennett, Cooper, Decherd, Dodd, Ettlinger, H. L. Holmes, Horton, Hulse, Jacobs, Lubben, Mayne, D. E. Mitchell, R. L. Moore, Phenix, M. B. Porter, P. K. Rees, W. A. Rees, Vandiver, G. R. West.
BEAUMONT. M. A. Campbell.
BOERNE. Hathaway.
BROWNSVILLE. de la Garza.
BROWNWOOD. Gayden, McClelland.
CANYON. L. G. Allen.
COLLEGE STATION. F. Ayres, A. A. Blumberg, Halperin, McKee, Whyburn.
COMMERCE. Cowling.
DALLAS. Dice, Hammer, Hartsfield, E. H. Jones, Mahoney, Seale.
DENTON. M. C. Brown, H. Porter.
FORNEY. Benson.
FORT WORTH. Estes, Hargett, Howard, E. R. Tucker.
GALVESTON. Burrell, P. H. Underwood.
GEORGETOWN. Wunder.
HOUSTON. Bray, Dean, G. C. Evans, L. R. Ford, E. O. Lovett, Michal.
LOCKNEY. Ewing.
MILFORD. Durham.
NACOGDOCHES. C. E. Ferguson.
PORT ARTHUR. G. S. Smith.
SAN ANGELO. Hagelstein.
SAN ANTONIO. McNelly, Roach.
SAN MARCOS. J. S. Brown, Sewell.
SHERMAN. May.
STEPHENVILLE. McSweeny, Redden.
WACO. Harrell, W. A. Nelson.
WICHITA FALLS. B. T. Adams.

UTAH. (8)

LEWISTON. Van Orden.
MORONI. Olsen.
PROVO. O. P. Barnett.
SALT LAKE CITY. J. L. Gibson, Horsfall, Marthakis, Pehrson, Unseld.

VERMONT. (7)

BURLINGTON. Donahue, Millington, Swift, E. Thomas.
MIDDLEBURY. Hazeltine, L. R. Perkins.
NORTHFIELD. Flanders.

VIRGINIA. (33)

ABINGDON. V. L. Wright.
ASHLAND. T. McN. Simpson.
BLACKSBURG. Brodie, Gudheim, O'Shaughnessy, J. E. Williams.
BRIDGEWATER. Shull.
CHARLOTTESVILLE. F. A. Wells.
CLIFTON STATION. O. Stone.
EAST RADFORD. Bowers.
EMORY. J. S. Miller.
FARMVILLE. Taliaferro.
HOLLINS. Dickinson.
LANGLEY FIELD. Hemke.
LEXINGTON. L. W. Smith, C. W. Watts, Witt.
LYNCHBURG. Larew, Pattillo, B. Russell.
MARION. Henna.
MONTEREY. Colaw.
RICHMOND COLLEGE. Gaines.
ROANOKE. Whaley.
SALEM. Carpenter.
SOUTH HILL. B. F. Walton.
SWEET BRIAR. Morenus, Searle.
UNIVERSITY. W. H. Echols, Luck, Thornton.
UNIVERSITY OF RICHMOND. I. Harris.
WILLIAMSBURG. Rowe.

WASHINGTON. (18)

ABERDEEN. V. Young.
CONNELL. Hays.
EVERETT. Robb.
LA CONNER. L. G. Butler.
PULLMAN. G. H. Freeman, Isaacs.
SEATTLE. E. T. Bell, Biggerstaff, Caffrey, Cramlet, Jerbert, Moritz, Mullemeister, Neikirk, Stager.
TACOMA. Hanawalt.
WALLA WALLA. Bratton, Eells.

WEST VIRGINIA. (11)

BETHANY. Cramblet.
BRIDGEPORT. Slawter.
HUNTINGTON. Hackney.
KEYSER. Fisher.
MORGANTOWN. M. Buchanan, Colwell, H. A. Davis, Eiesland, C. N. Reynolds, B. M. Turner.
WILLIAMSON. Romig.

WISCONSIN. (33)

ASHLAND. Kendrigan.
BELOIT. H. H. Conwell, Huffer, Suydam.
MADISON. F. E. Allen, Bunyan, Dowling, Dresden, Feltges, W. W. Hart, Ingraham, E. B. Miller, Pollard, Skinner, Slichter, Stout, Van Vleck, W. Weaver.
MILTON. A. E. Whitford.
MILWAUKEE. Atwater, Ericson, P. H. Evans, Frumveller, Morrissy, Quarles, C. G. Simpson.
PLATTEVILLE. Warner.
RIPON. Woodmansee.
RIVER FALLS. McMillan.
SOUTH MILWAUKEE. Hoar.
SUPERIOR. C. W. Smith.
WEST ALLIS. Roth.
WEST DE PERE. DeCleene.

WYOMING. (4)

LARAMIE. Bellamy, Fitterer, Gossard, Rechard.

FOREIGN MEMBERS. (Other than Canada.)

ARGENTINE. (2)

BUENOS AIRES. Baidaff, Broggi.

BELGIUM. (1)

LIEGE. Van Hee.

BULGARIA. (1)

LOVETCH. E. M. Perry.

CHINA. (7)

CANTON. W. F. MacDonald.
CHANGSHA. Leavens.
PEKING. Heinz, Konantz.
SHANGHAI. Ely.
TANGSHAN. Patten.
TIENTSIN. Chin.

FRANCE. (5)

BESANÇON. Lebeuf.
NANCY. Gérardin.
PARIS. Borel, Hadamard.
STRASBOURG. Fréchet.

GERMANY. (1)

GÖTTINGEN. Coates.

GREAT BRITAIN. (7)

CAMBRIDGE. Ball, P. W. Wood.
EDINBURGH. Horsburgh.
HOVE. Chepmell.
OXFORD. Hardy, W. E. Robertson, Strom.

INDIA. (4)

ALLAHABAD CITY. Mitra.
CALCUTTA. Bose, Dey.
VEDARANIAM. Ramana-Sastrin.

ITALY. (6)

BOLOGNA. Bortolotti, Enriques, Pincherle.
CATANIA. Cipolla.
PISA. Bianchi.
TURIN. Fubini.

JAPAN. (3)

PYENGYANG. Parker.
TOKYO. Mikami, Ono.

NEW ZEALAND. (1)

DUNEDIN. Martyn.

POLAND. (1)

WARSAW. Dickstein.

PORTUGAL. (1)

LISBON. da Cunha.

SOUTH AFRICA. (3)

BLOEMFONTEIN. Arndt.
JOHANNESBURG. Dalton.
RONDEBOSCH. Muir.

SPAIN. (1)

MADRID. de Toledo.

SWEDEN. (1)

LUND. Craig.

SWITZERLAND. (3)

FRIBOURG. Bays.
GENEVA. Fehr.
NEUCHATEL. DuPasquier.

SYRIA. (1)

BEIRUT. Jurdak.

TURKEY. (2)

CONSTANTINOPLE. A. F. Johnson, Mourad.

UKRAINE. (1)

KIEFF. Kryloff.

RECAPITULATION OF MEMBERSHIP.

Individual members November 15, 1924	1,712	
Institutional members November 15, 1924	110	
Total membership November 15, 1924		1,822
Total membership November 1, 1922		1,476

CHARTER MEMBERSHIP.

Individual charter members	1,045	
Institutional charter members	52	
Total charter membership		1,097
Net gain in individual members	667	
Net gain in institutional members	58	
Total net gain over charter membership		725
Total net gain since November 1, 1922		346

BY-LAWS OF THE MATHEMATICAL ASSOCIATION OF AMERICA (INCORPORATED).

(As amended and adopted by unanimous vote at a special meeting of members called for the purpose at Rochester, N. Y., September 7, 1922, a quorum being present.)

ARTICLE I—NAME, PURPOSE AND CORPORATE SEAL.

1. This organization shall be known as

THE MATHEMATICAL ASSOCIATION OF AMERICA (INCORPORATED).

2. Its object shall be to assist in promoting the interests of mathematics in America, especially in the collegiate field, by holding meetings in any part of the United States or Canada for the presentation and discussion of mathematical papers, by the publication of mathematical papers, journals, books, monographs and reports, by conducting investigations for the purpose of improving the teaching of mathematics, by accumulating a mathematical library and by coöperating with other organizations whenever this may be desirable for attaining these or similar objects.

3. The Corporate Seal of the Association shall have inscribed thereon the name of the Association and the words "Corporate Seal—Illinois."

ARTICLE II—MEMBERSHIP.

1. Any person who is interested in the field of collegiate mathematics shall be eligible for election to membership in the Association.

2. Any institution in which the Calculus is regularly taught shall be eligible for election to institutional membership in the Association. Such an institution shall have the privilege of sending a voting delegate to the meetings of the Association.

3. Election to membership shall be by vote of the Board upon written application from the individual or institution seeking admission, endorsed in the case of individuals by two members of the Association.

4. Those who were admitted to membership in The Mathematical Association of America (unincorporated) prior to October 1, 1920, and were in good standing as such on that date, were thereby admitted to membership in this Association (Incorporated).

ARTICLE III—BOARD OF TRUSTEES AND OFFICERS.

1. The Officers of the Association shall be a President, two (2) Vice-Presidents, a Secretary-Treasurer, a Librarian and three (3) members of a Committee on Official Journal.

2. The control and management of the affairs and funds of the Association shall be vested in a Board of twenty (20) Trustees (hereinafter called the "Board"), who shall be members of the Association. This Board shall consist of the officers of the Association and twelve (12) additional members.

3. The President and Vice-Presidents shall be elected by the Association's members annually for a term of one year, and four members of the Board shall be elected by the Association's members annually for a term of three years. They shall be eligible for reëlection, but not for more than two (2) consecutive terms. The Secretary-Treasurer, the Librarian, and the Committee on Official Journal, consisting of the Editor-in-Chief, the Manager and one other member, shall be appointed by the Board. All Officers and other Trustees shall hold over until their respective successors are elected or appointed and qualify.

4. The Board shall transact the official business of the Association and shall report its actions at the annual business meeting of the Association and in the official journal. A statement regarding any proposed action of the Board which makes or alters a question of policy shall be published in the official journal, or notice of such proposed action shall be mailed to each member, before final action has been taken, so that members of the Association may make known to the Board their individual views.

5. The Board shall have authority to fill vacancies *ad interim* in any office, including vacancies in the Board and in the Committee on Official Journal, and to make any other appointments necessary for the transaction of the business of the Association.

6. At all meetings of the Board of Trustees a quorum shall consist of not less than five (5) members and no business may be validly transacted at a meeting at which less than a quorum is present; *provided* that any meeting of the Board, whether or not a quorum be present, may be

adjourned to a specified time and place by a majority of the members present without notice to the members at large other than announcement at such meeting. Informal action based on a mail ballot by the members of the Board, if ratified at a properly convened meeting of the Board, shall be as valid and effective as if originally authorized at such meeting.

7. Approximately two months before the date of the annual meeting all members shall be given an opportunity to nominate by mail a candidate for each office to be filled by the members for the ensuing year. Approximately one month before the annual meeting the Board shall announce two candidates for each office to be filled by the members, one being the person who received the highest vote in the nominations and the other being selected from among the several nominees next in order. The election shall be by mail or in person and shall close on the day of the annual meeting.

8. The President shall be the Executive Officer of the Association, shall preside at all meetings of the Board of Trustees and at the annual meeting of the Association. He shall have the usual duties pertaining to his office and such other duties as may from time to time be assigned him by the Board of Trustees.

9. The Vice-Presidents shall, in the absence of the President, have and exercise the powers of the President, their order being determined alphabetically. The Board of Trustees may assign to the Vice-Presidents such duties as may from time to time be determined.

10. The Secretary-Treasurer shall have the usual duties pertaining to the office of Secretary and of Treasurer, including the custody of the records of the Association and of its Corporate Seal, the keeping of minutes of the meetings of the Board of Trustees and of the annual meeting and special meetings of members, and giving of due notice of all regular and special meetings of the Association and of the Board of Trustees and the supervision and safe-keeping of the funds of the Association. The Secretary-Treasurer shall also have the duty of seeing that whenever Trustees are elected, including the election of Trustees to fill vacancies, a Certificate, under the Seal of the Association, giving the names of those elected and the term of their office, shall be recorded in the Office of the Recorder of Deeds for Cook County, Illinois. Such Certificate shall be signed by the Secretary-Treasurer and verified by oath of the President.

11. The Committee on Official Journal shall have supervision of the official journal subject to the control of the Board of Trustees.

12. The Librarian shall have general charge of the library of the Association and shall direct its affairs, including the exchange of the publications of the Association, subject to the control of the Board.

Article IV—Meetings.

1. A meeting of the Association shall be held annually, at such time and place as the Board may direct. Special meetings of the Association may be called from time to time by the Board, or while the Board is not in session by the President of the Association, to be held at such time and place as may appear from the call.

2. The outgoing Board shall hold a meeting immediately preceding the annual meeting of the Association next succeeding their election, and the members of the new Board shall hold a meeting and organize, by completing the Board, immediately succeeding the annual meeting of the Association at which the new members thereof were elected. Further meetings of the Board may be held from time to time at the call of the President or of any three (3) members of the Board.

3. Notice of any meeting of members of the Association shall be given by the Secretary-Treasurer at least thirty (30) days prior to the date set for such meeting. Notice of all meetings of the Board other than the regular meetings provided in Section 2 shall be given to each member of the Board at least fifteen (15) days prior to the date set therefor.

4. Any member of the Association or of the Board may waive notice with the same effect as if due notice had been given him.

5. At all meetings of the Association a quorum shall consist of not less than twenty-five (25) members and no business may be validly transacted at a meeting at which less than a quorum is present; *provided* that any meeting of the Association, whether or not a quorum be present, may be adjourned to a specified time and place by a majority of the members present without notice to the members at large other than the announcement at such meeting.

6. Members may take part and vote in person or by proxy at all meetings of the Association.

Article V—Sections.

1. Any group of not less than ten (10) members of this Association may petition the Board for authority to organize a Section of the Association for the purpose of holding local meetings.

The Board shall have power to specify the conditions under which such authority shall be granted.

2. The Association shall not be obligated to pay from its treasury any of the expenses of such Sections.

ARTICLE VI—OFFICIAL PUBLICATIONS.

1. The Association shall publish an official journal, which shall be sent free to all members of the Association in accordance with Article VII.

2. The Board shall have full control of the publication and sale of the official journal and of all other official publications.

3. The official journal shall be under the general management of the Committee on Official Journal. There shall also be appointed by the Board a body of Associate Editors who shall give assistance in connection with the official journal and under the direction of the Committee on Official Journal.

4. The Board shall from time to time, as the need arises, make special provision for the management of any other official publications.

5. The Board shall fix the price of the official journal and of any other official publications of the Association, but in no case shall the journal be sold to non-members for less than the annual dues of individual members.

ARTICLE VII—DUES.

1. Individual members of the Association shall pay an initiation fee of Two Dollars ($2) at the time of election.

2. The annual dues of each individual member shall be Four Dollars ($4), including a subscription to the official journal.

3. The annual dues of each institutional member shall be Seven Dollars ($7), including two (2) subscriptions to the official journal.

4. All dues shall be payable on the first of January of each year. Should the annual dues of any member remain unpaid beyond a reasonable time, his name shall be dropped from the listl after due notice.

5. New members entering the Association after April 1 of any year shall have their dues pro rated for the balance of the year, except when they desire to receive the full current volume of the official journal.

6. The life membership fee shall be the present value, according to McClintock's Male Annuitant Table based upon four (4) per cent. interest, of an annuity due of Four Dollars ($4) a year at the attained age of the member; an annual valuation of the life membership fund shal, be made under the McClintock Male Four (4) Per Cent. Table; and the reserve thus computed shall be held as a liability.

ARTICLE VIII—AMENDMENTS TO THE ARTICLES OF ASSOCIATION AND BY-LAWS.

1. Changes in the Articles of Association or amendments to the By-Laws may be made at any annual meeting of the Association, or at any adjourned session thereof, or at any special meeting of the Association called for such purpose, by a two-thirds (⅔) vote of those present and entitled to vote; *provided* that due notice concerning such amendment shall have been printed in the official journal, or mailed to each member, at least one (1) month before the date of such meeting.

2. No changes in the Articles of Association shall have legal effect until a certificate thereof, verified by oath of the President and under Seal of the Association, attested by the Secretary-Treasurer, shall be filed in the office of the Secretary of State of the State of Illinois and recorded in the office of the Recorder of Deeds for Cook County, Illinois.

PERIODS OF SERVICE OF THE OFFICERS OF THE ASSOCIATION.

PRESIDENTS.

E. R. HEDRICK 1916
FLORIAN CAJORI 1917
F. V. HUNTINGTON 1918
H. E. SLAUGHT 1919
D. E. SMITH 1920
G. A. MILLER 1921
R. C. ARCHIBALD 1922
R. D. CARMICHAEL 1923
H. L. RIETZ 1924

VICE-PRESIDENTS.

E. V. HUNTINGTON 1916
D. A. MILLER 1916
G. N. LEHMER 1917, 1918
OSWALD VEBLEN 1917
J. W. YOUNG 1918
R. G. D. RICHARDSON 1919
H. L. RIETZ 1919
HELEN A. MERRILL 1920
E. J. WILCZYNSKI 1920
R. C. ARCHIBALD 1921
R. D. CARMICHAEL 1921, 1922
B. F. FINKEL 1922
A. B. CHACE 1923
L. P. EISENHART 1923
J. L. COOLIDGE 1924
DUNHAM JACKSON 1924

SECRETARY-TREASURER.

(Appointed by the Council or Board after 1918.)

W. D. CAIRNS 1916–

COMMITTEE ON PUBLICATIONS.

(Appointed by the Council or Board.)

H. E. SLAUGHT 1916–
R. D. CARMICHAEL 1916–1918
W. H. BUSSEY 1916–1918
R. C. ARCHIBALD 1919–1921
W. A. HURWITZ 1919–1921
A. A. BENNETT 1922
H. P. MANNING 1922
W. B. FORD 1923–
J. L. COOLIDGE 1923
A. J. KEMPNER 1924

ELECTED MEMBERS OF THE COUNCIL OR BOARD.

D. N. LEHMER 1916–1918, 1922–
R. E. MORITZ 1916–1918
K. D. SWARTZEL 1916
OSWALD VEBLEN 1916, 1920–1922
R. C. ARCHIBALD 1916–1917, 1923–
FLORIAN CAJORI 1916, 1918–1923
M. B. PORTER 1916–1917
J. W. YOUNG 1916–1917, 1920–1922
B. F. FINKEL 1916–1921
E. H. MOORE 1916–1921, 1923–
J. N. VAN DER VRIES 1916–1918
ALEXANDER ZIWET 1916–1918
E. R. HEDRICK 1917–1922, 1924–
HELEN A. MERRILL 1917–1919
D. E. SMITH 1917–1919, 1921–
ELIZABETH B. COWLEY 1918–1920
G. A. MILLER 1918–1920, 1922–
E. J. WILCZYNSKI 1918–1919, 1922–
L. P. EISENHART 1919–1922
E. V. HUNTINGTON 1917, 1919–
E. L. DODD 1920
R. D. CARMICHAEL 1920, 1924–
A. A. BENNETT 1921
H. L. RIETZ 1921–1923
C. F. GUMMER 1921–
A. B. CHACE 1924–
DUNHAM JACKSON 1923
CLARA E. SMITH 1923–

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By H. S. EVERETT, Bucknell University.

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